

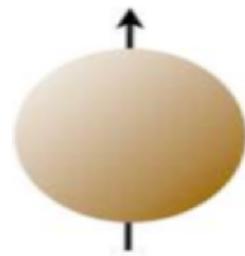
Hadron Structure

EIC Advisory Committee Meeting
Feb 28 - March 1, 2014

Haiyan Gao – Duke University
Jianwei Qiu – Brookhaven National Lab
(Presented by Jianwei Qiu)



What is inside the proton/neutron?



What is inside the proton/neutron?

1933: Proton's magnetic moment

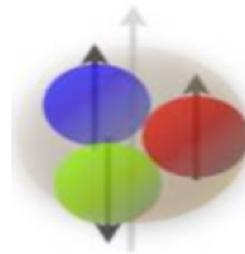


Nobel Prize
In Physics 1943

Otto Stern

"for ... and for his discovery of the magnetic moment of the proton".

$$g \neq 2$$



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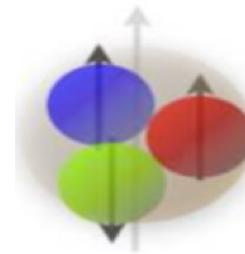
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"for ... and for his thereby achieved discoveries concerning the structure of the nucleons"

Form factors → Charge distributions

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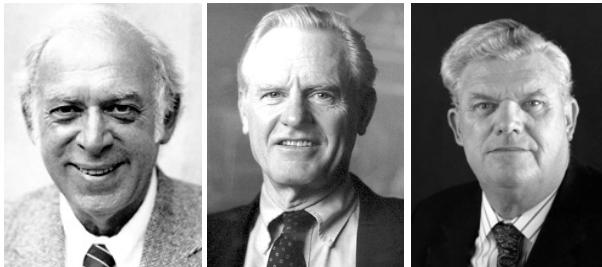


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1969: Deep inelastic e-p scattering



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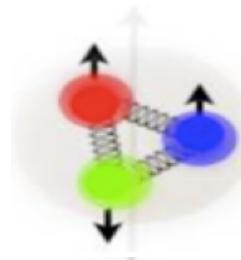
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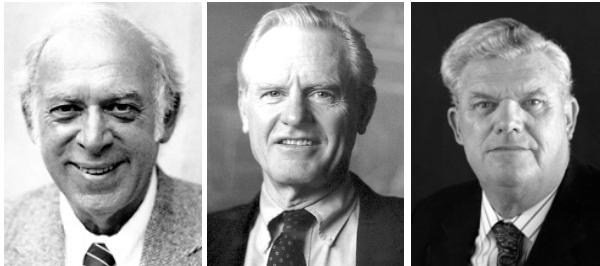


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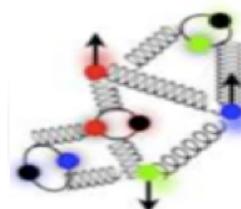
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Form factors → Charge distributions

1974: QCD Asymptotic Freedom



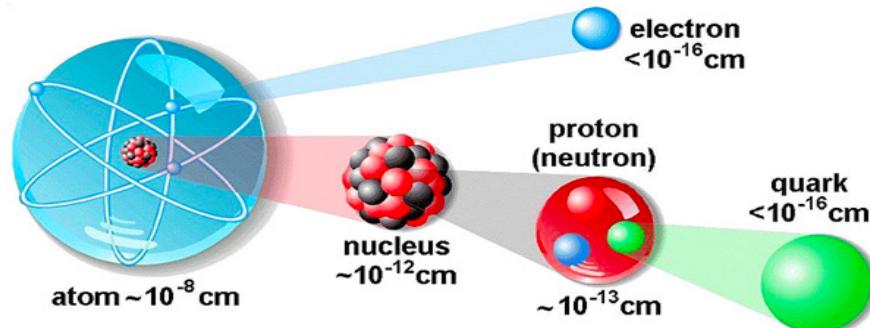
Nobel Prize in Physics 2004

David J. Gross, H. David Politzer, Frank Wilczek

"for the discovery of asymptotic freedom in the theory of the strong interaction".

Hadron structure

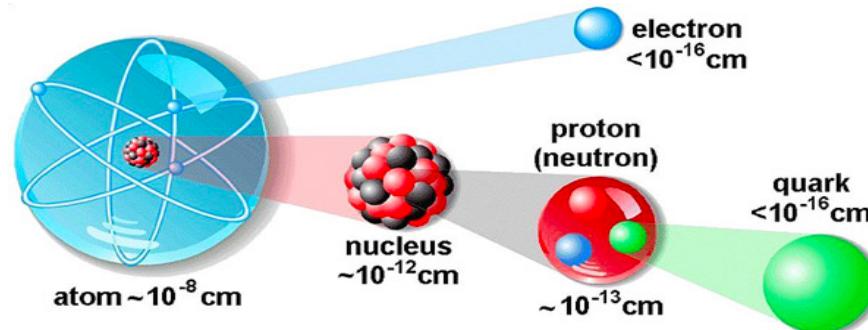
□ Atomic structure:



- ✧ Discovery of Quantum Physics
- ✧ Discovery of the nucleus:
 - Localized charge/mass center
 - Core of all visible matter

Hadron structure

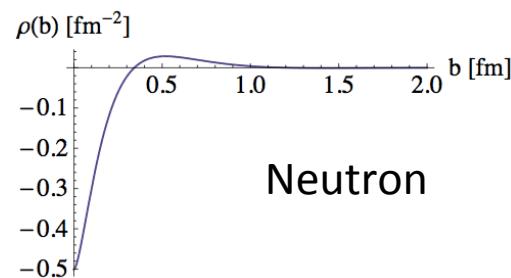
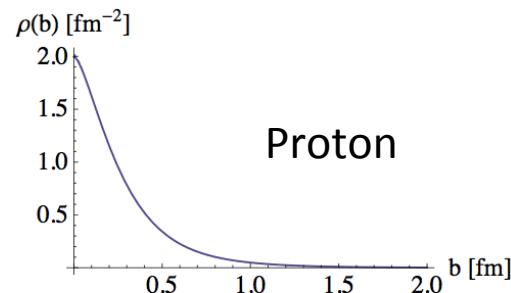
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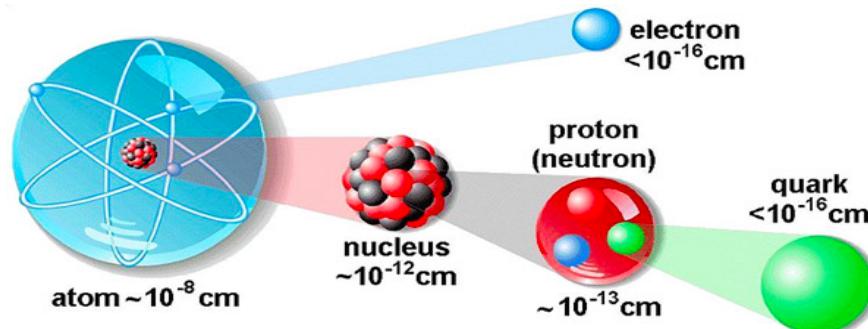
□ Structure of nucleons?

✧ Electric charge distribution:



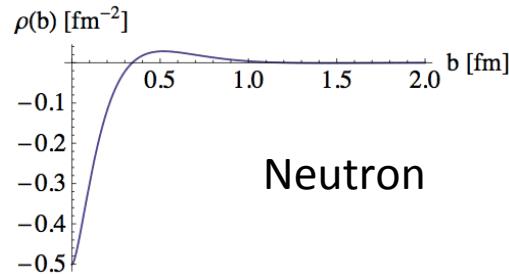
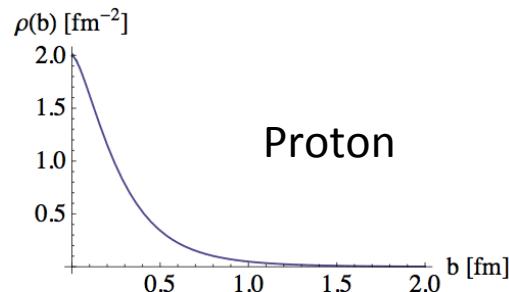
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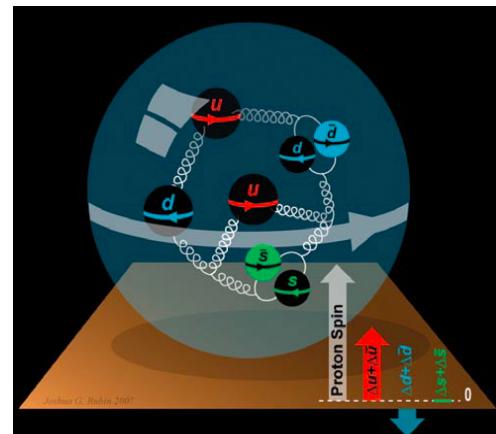


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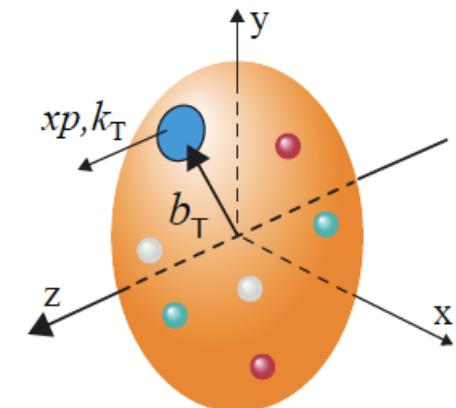
✧ Spin decomposition? Spin-motion correlation?



✧ Discovery of Quantum Physics

✧ Discovery of the nucleus:

- Localized charge/mass center
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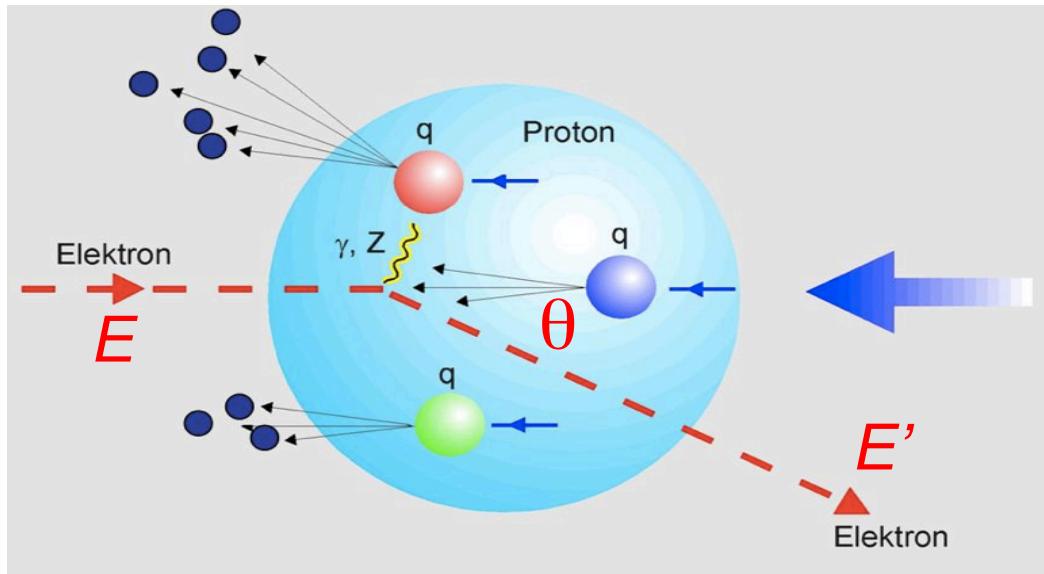


Calibrated 3D probes?

Electron-Ion Collider (EIC)

See talk by Meziani

- Powerful microscope (with an extra knob – spin):



- ❖ Localized probe:

$$Q^2 = -(p - p')^2 \gg 1 \text{ fm}^{-2}$$

➡ $\frac{1}{Q} \ll 1 \text{ fm}$

- ❖ Two variables:

$$Q^2 = 4EE' \sin^2(\theta/2)$$
$$x_B = \frac{Q^2}{2m_N\nu}$$
$$\nu = E - E'$$

- DIS (inclusive, semi-inclusive, exclusive):

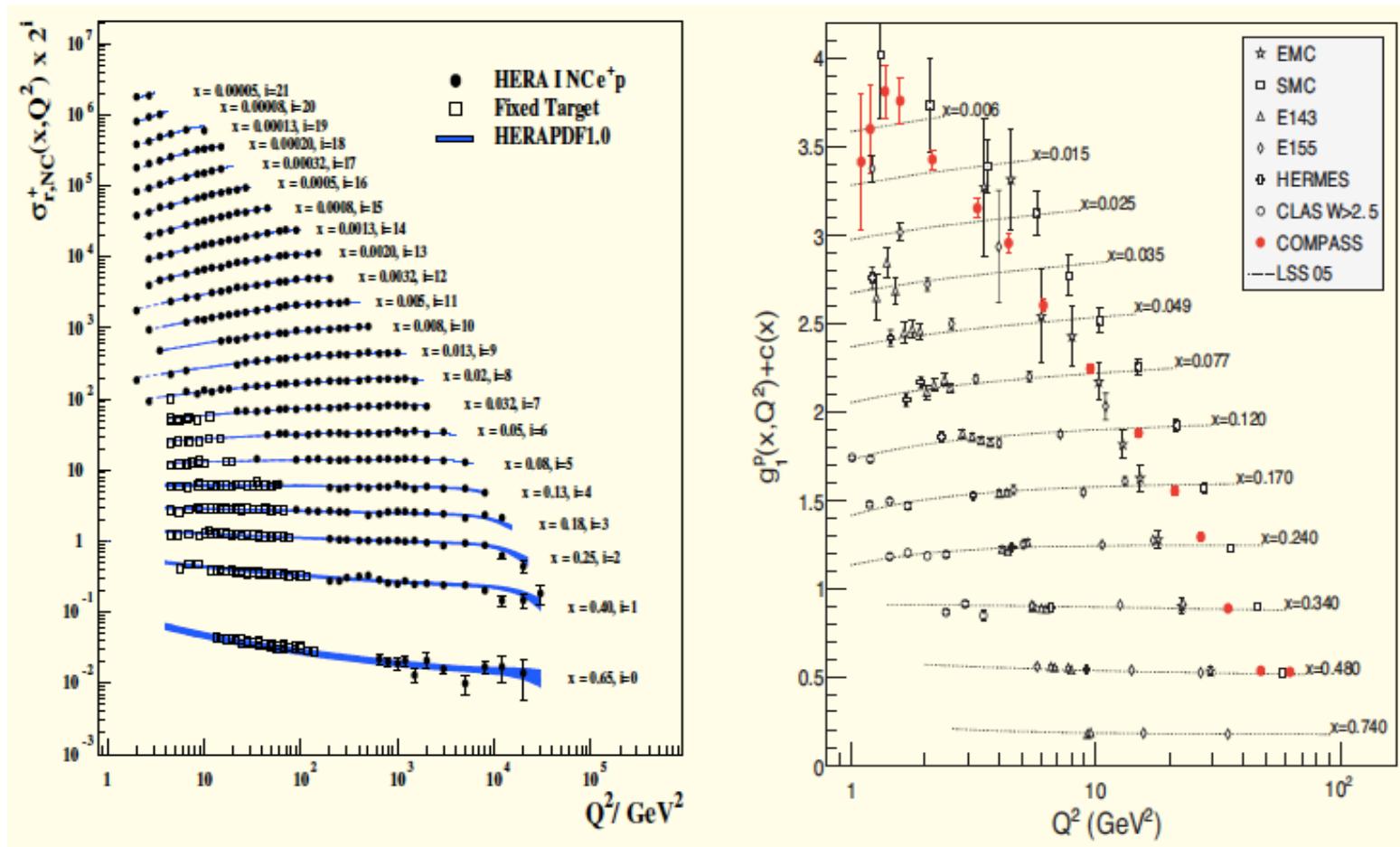
- ❖ A machine at *the frontier of polarized luminosity, combined with versatile kinematics and beam species* – a bright sub-femtometer scope
- ❖ Allow many fundamental and challenge QCD questions to be tackled at a *single facility*
- ❖ A machine to *cat-scan* a hadron in 3D with $1/Q$ resolution, ...
- ❖ A user facility *reaches out* every branches of nuclear science

Inclusive DIS

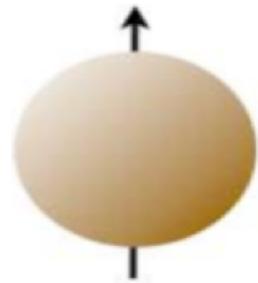
- Structure functions ($F_2, F_L, g_1, g_2, \dots$):

 - ❖ Single hard scale Q – *Theory: Collinear QCD factorization*
 - ❖ 1D - PDFs to connect QCD parton dynamics to DIS cross sections

- Current status:



The incomplete nucleon: spin puzzle



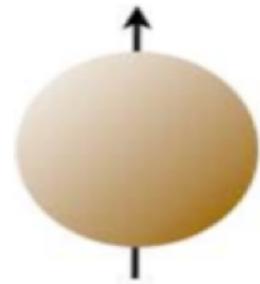
Proton Spin

Jaffe-Manohar, 90
Ji, 96

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + (L_q + L_g)$$

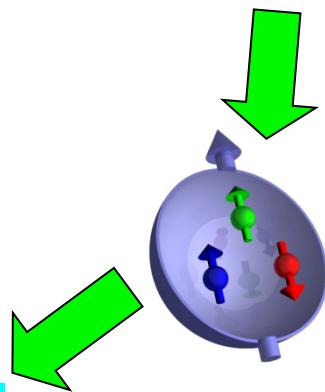
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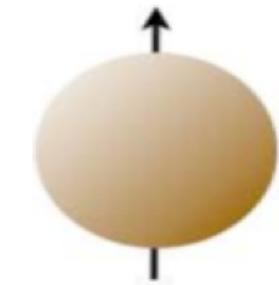
Quark helicity
Best known

$$\frac{1}{2} \int dx (\Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s})$$

~ 30%

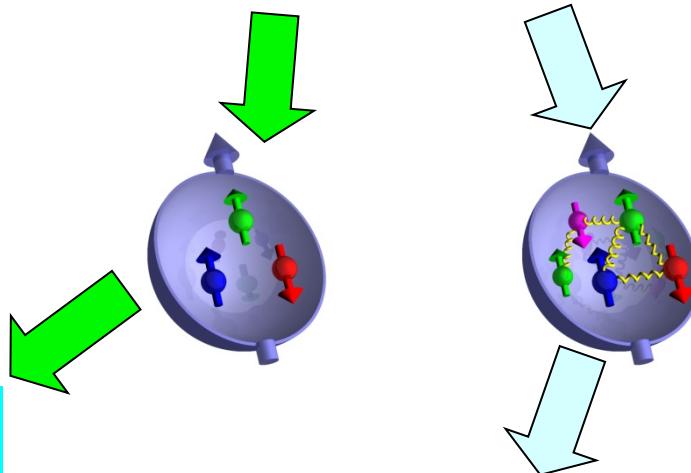
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Quark helicity
Best known

Gluon helicity
Start to know

$$\frac{1}{2} \int dx (\Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s})$$

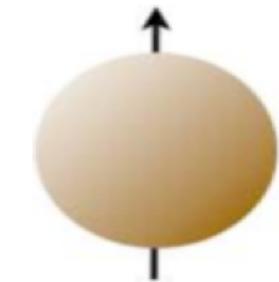
$\sim 30\%$

$$\Delta G = \int dx \Delta g(x)$$

$\sim 20\%$ (STAR Data)

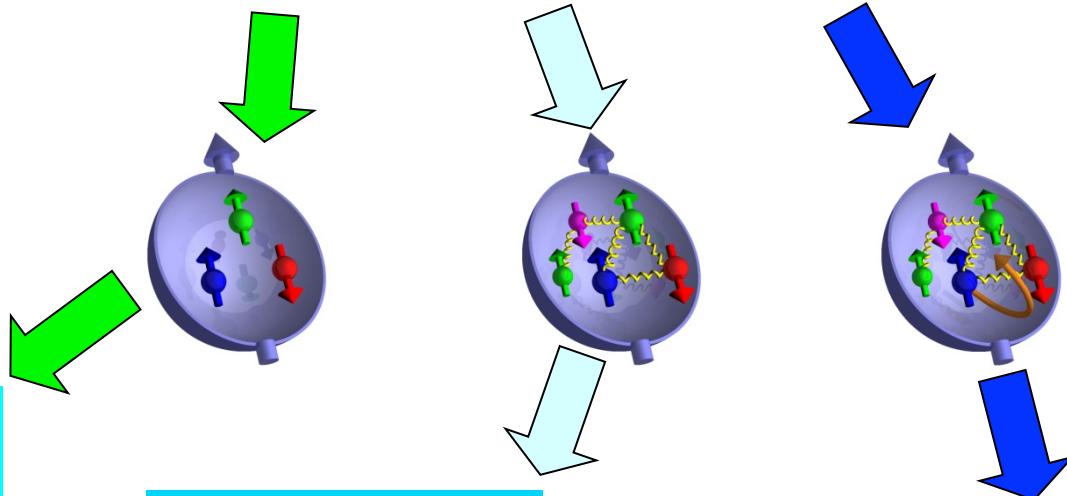
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Proton Spin

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + (L_q + L_g)$$



Quark helicity
Best known

Gluon helicity
Start to know

Orbital Angular Momentum
of quarks and gluons
Little known

$$\frac{1}{2} \int dx (\Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s})$$

$\sim 30\%$

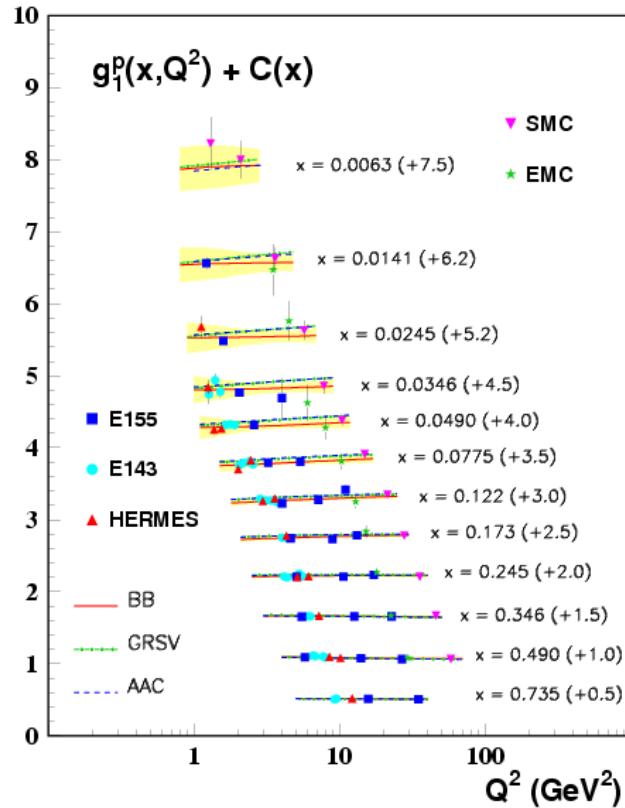
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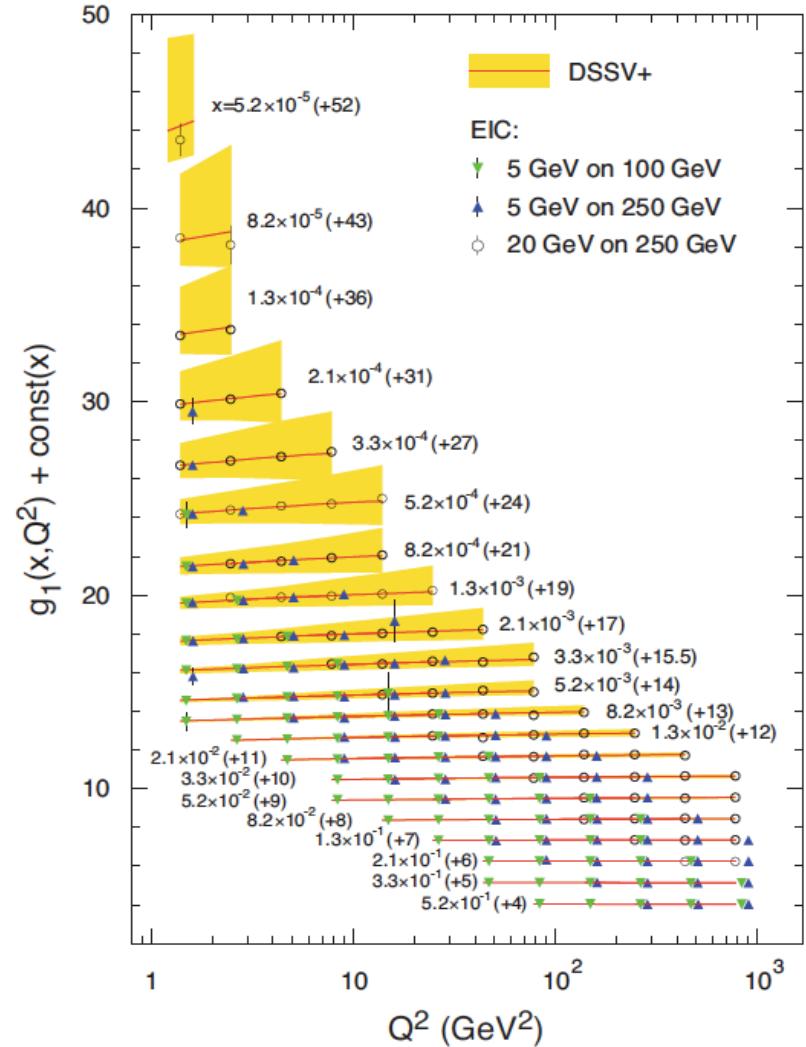
Net effect of partons'
transverse motion?

The power of EIC

□ Luminosity and coverage in x and Q^2 :



at EIC



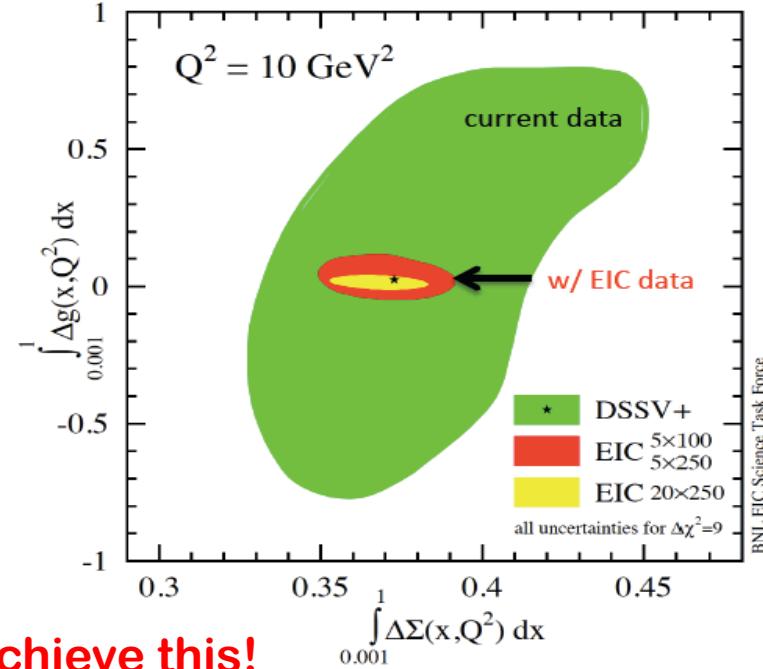
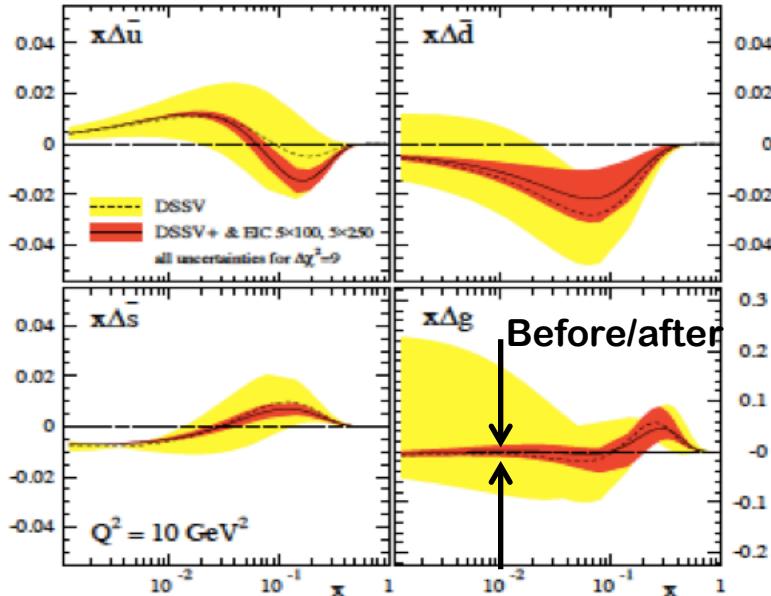
□ Reach out the glue:

$$\frac{dg_1(x, Q^2)}{d \ln Q^2} = \frac{\alpha_s}{2\pi} P_{qg} \otimes \Delta g(x, Q^2) + \dots$$

The decisive measurement

□ One-year of running at EIC:

Wider Q^2 and x range including low x at EIC!

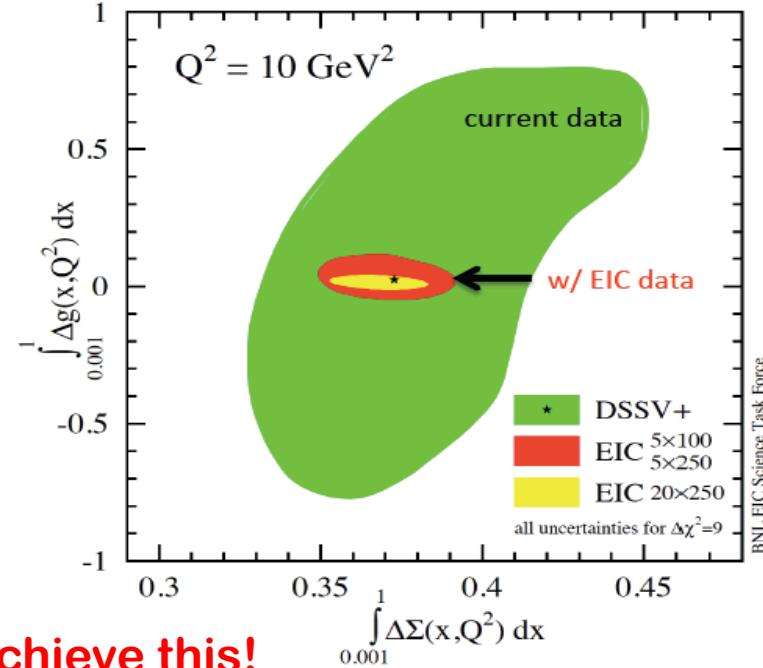
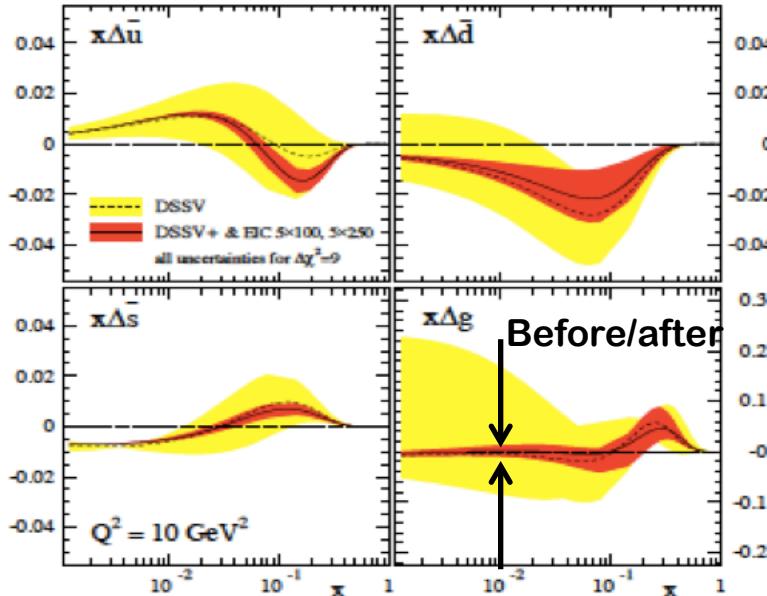


No other machine in the world can achieve this!

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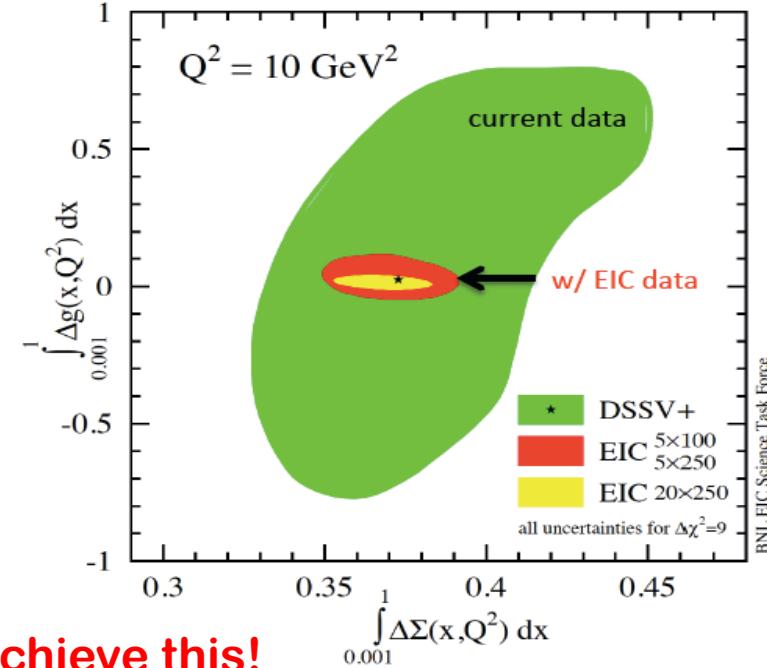
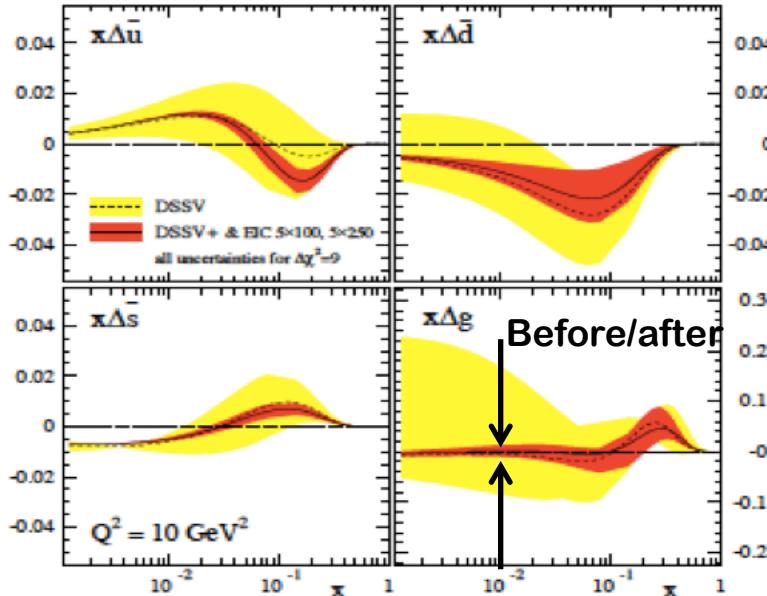
□ Ultimate solution to the proton spin puzzle:

- ✧ *Precision measurement of $\Delta g(x)$ – extend to smaller x regime*
- ✧ *Orbital angular momentum contribution – measurement of GPDs!*

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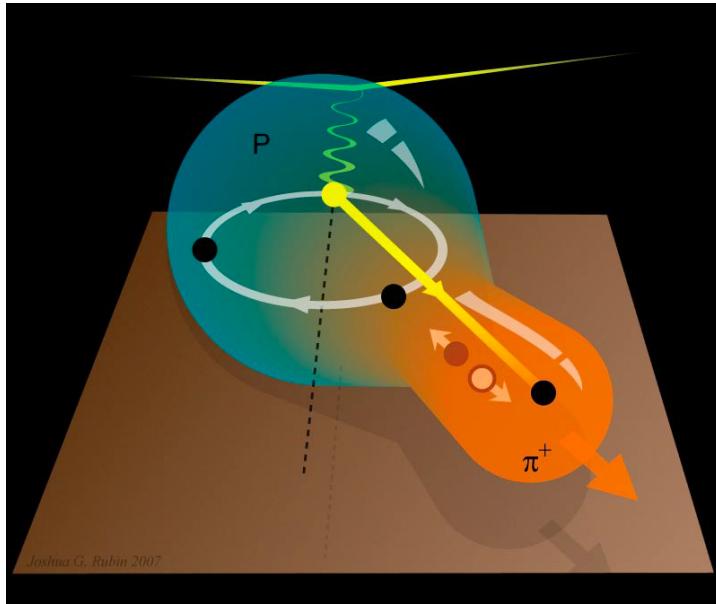
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Smaller x – Higher collision energy – Smaller electron scattering angle

Non-trivial detector requirements (see talks by Aschenauer & Nadel-Turonski)

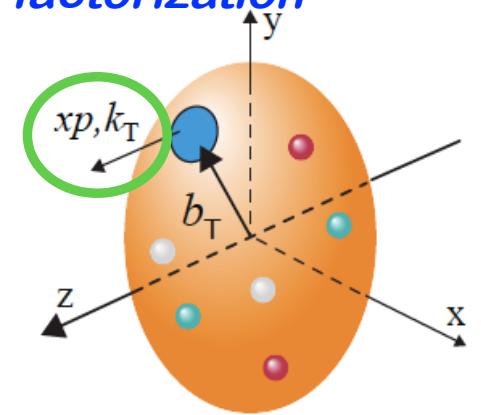
Semi-inclusive DIS



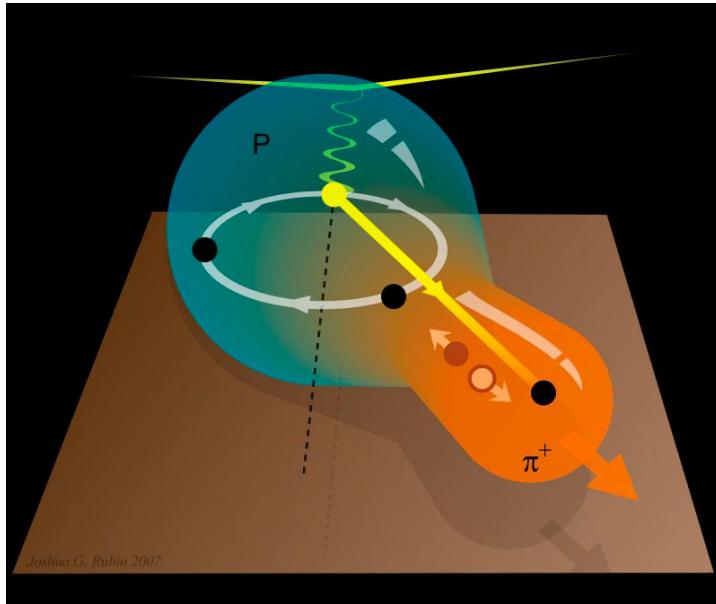
□ Naturally, two scales:

- ✧ high Q – localized probe
To “see” quarks and gluons
- ✧ Low p_T – sensitive to confining scale
To “see” their confined motion
- ✧ *Theory – QCD TMD factorization*

*Best process
to probe TMDs*



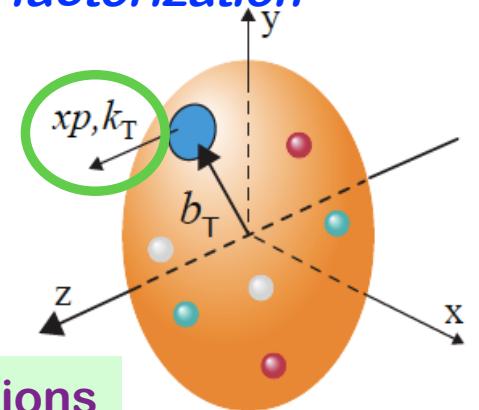
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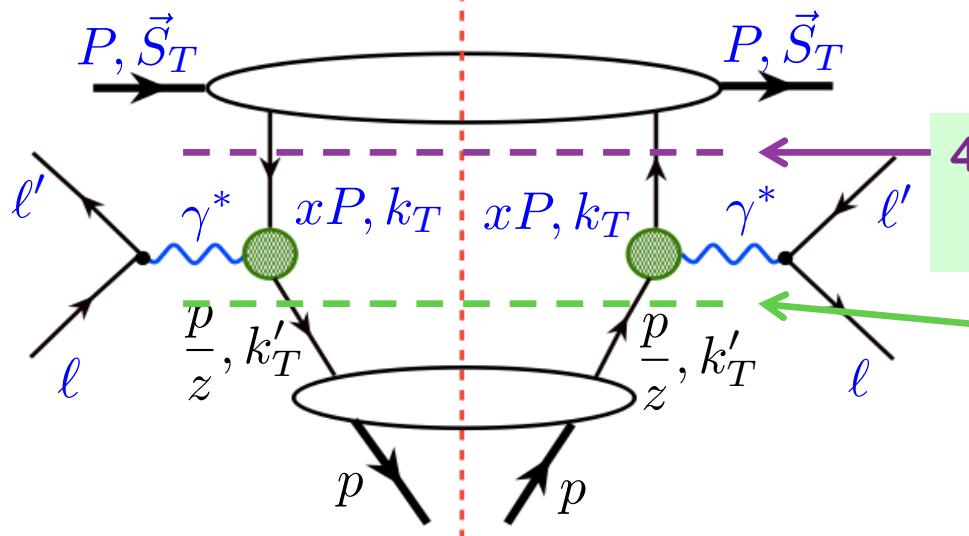
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□ Spin-motion correlation:



4 spin combinations
 $\gamma^+, \gamma^+\gamma_5, \gamma^+\gamma_\perp^\alpha$

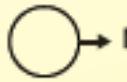
4 spin combinations
 $\gamma^+, \gamma^+\gamma_5, \gamma^+\gamma_\perp^\alpha$

TMDs – power of spin

□ Rich quantum correlations:

8 leading power (twist) quark TMDs:

		Quark Polarization		
		Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Nucleon Polarization	U	$f_1 = \bullet$		$h_1^\perp = \bullet - \bullet$ Boer-Mulders
	L		$g_{1L} = \bullet \rightarrow - \bullet \rightarrow$ Helicity	$h_{1L}^\perp = \bullet \rightarrow - \bullet \rightarrow$
	T	$f_{1T}^\perp = \bullet \uparrow - \bullet \downarrow$ Sivers	$g_{1T}^\perp = \bullet \uparrow - \bullet \uparrow$	$h_1 = \bullet \uparrow - \bullet \uparrow$ Transversity $h_{1T}^\perp = \bullet \uparrow - \bullet \uparrow$

 Nucleon Spin
  Quark Spin

Similar for gluons

EIC – the best for probing TMDs

- Naturally, two planes:

$$\begin{aligned}
 A_{UT}(\varphi_h^l, \varphi_s^l) &= \frac{1}{P} \frac{N^\uparrow - N^\downarrow}{N^\uparrow + N^\downarrow} \\
 &= A_{UT}^{Collins} \sin(\phi_h + \phi_s) + A_{UT}^{Sivers} \sin(\phi_h - \phi_s) \\
 &\quad + A_{UT}^{Pretzelosity} \sin(3\phi_h - \phi_s)
 \end{aligned}$$

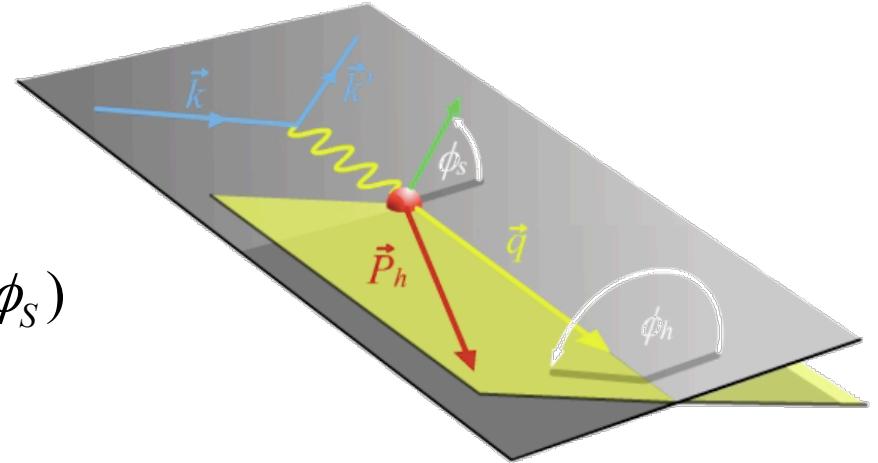
- Separation of TMDs:

$$A_{UT}^{Collins} \propto \langle \sin(\phi_h + \phi_s) \rangle_{UT} \propto h_1 \otimes H_1^\perp$$

$$A_{UT}^{Sivers} \propto \langle \sin(\phi_h - \phi_s) \rangle_{UT} \propto f_{1T}^\perp \otimes D_1$$

$$A_{UT}^{Pretzelosity} \propto \langle \sin(3\phi_h - \phi_s) \rangle_{UT} \propto h_{1T}^\perp \otimes H_1^\perp$$

Hard, if not impossible, to separate TMDs in hadronic collisions



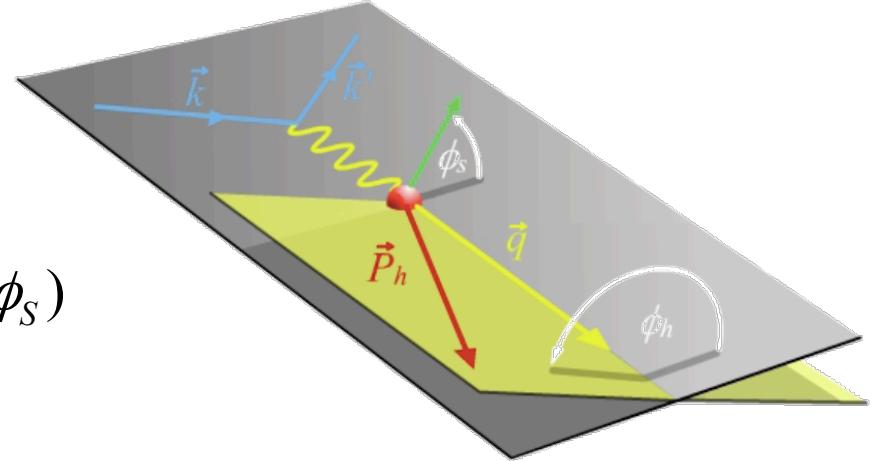
Collins frag. Func.
from e^+e^- collisions



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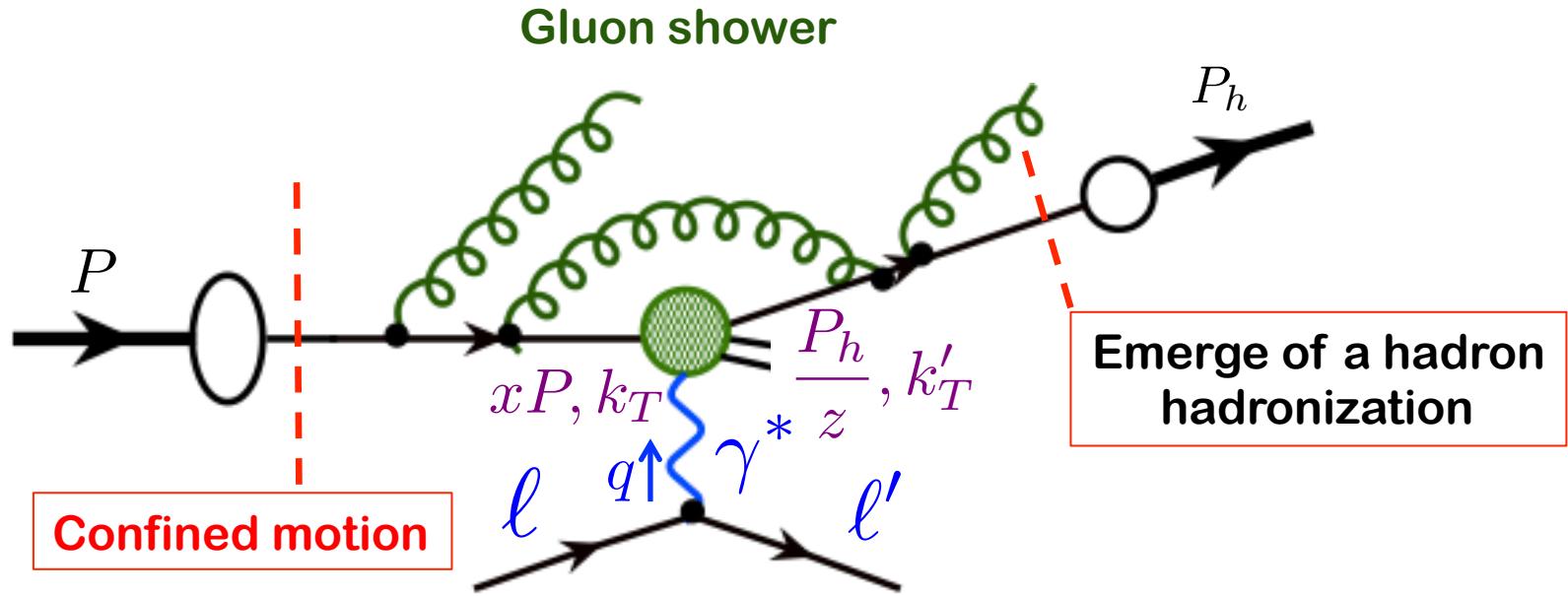
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SIDIS SSAs depend on 4-D variables (x, Q^2, z and P_T)

Large angular coverage and precision measurement of
asymmetries in 4-D phase space is essential

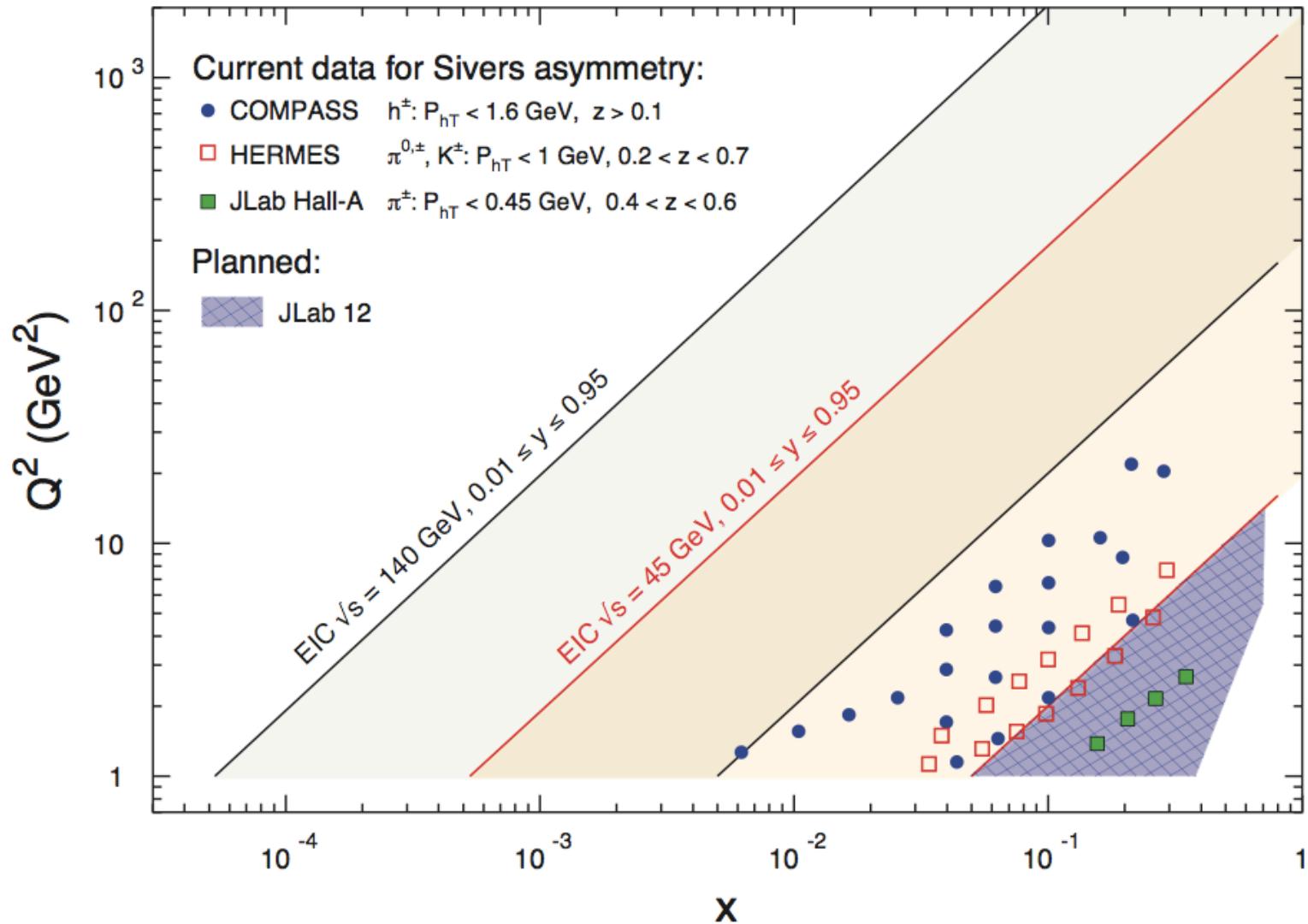
Confined motion of quarks and gluons

- Sources of parton k_T at the hard collision:



- ✧ Q^2 evolution – test of QCD perturbative dynamics
- ✧ Low p_T – wide x coverage – confined motion
- ✧ Particle ID – flavor separation of the sea
- ✧ ...

EIC coverage on TMDs



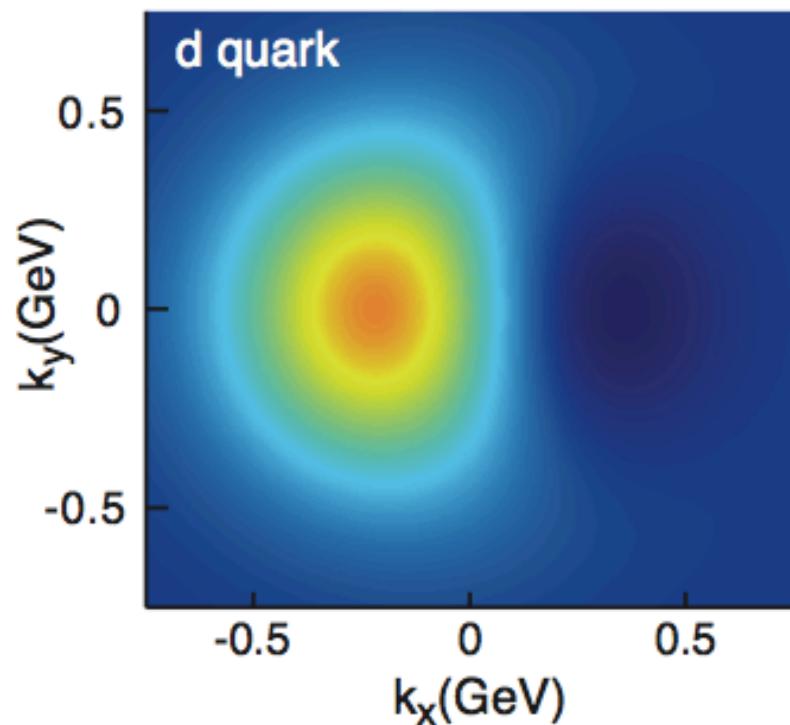
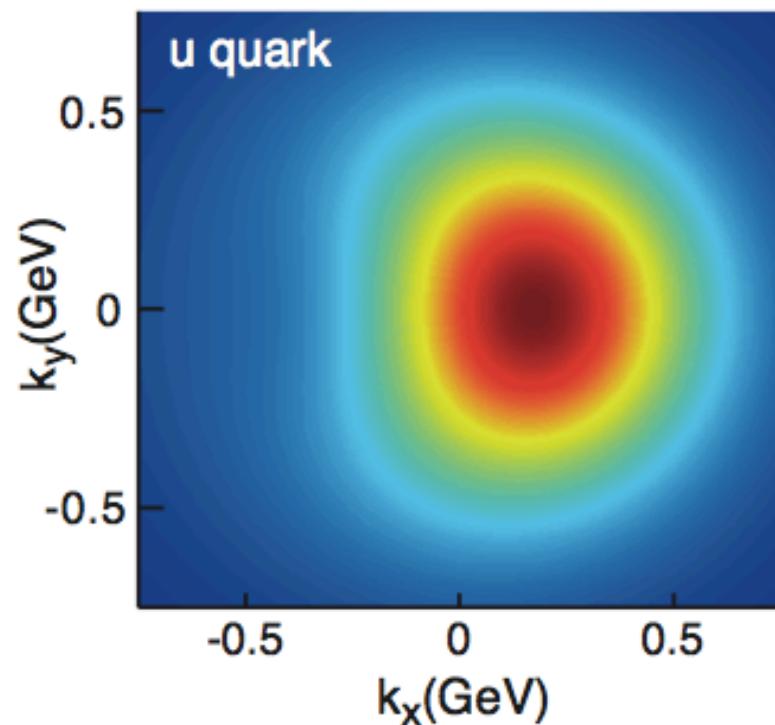
First, maybe only, measurement of polarized sea and gluon TMDs

Valence quark TMDs

- Sivers function @ $x = 0.1$:

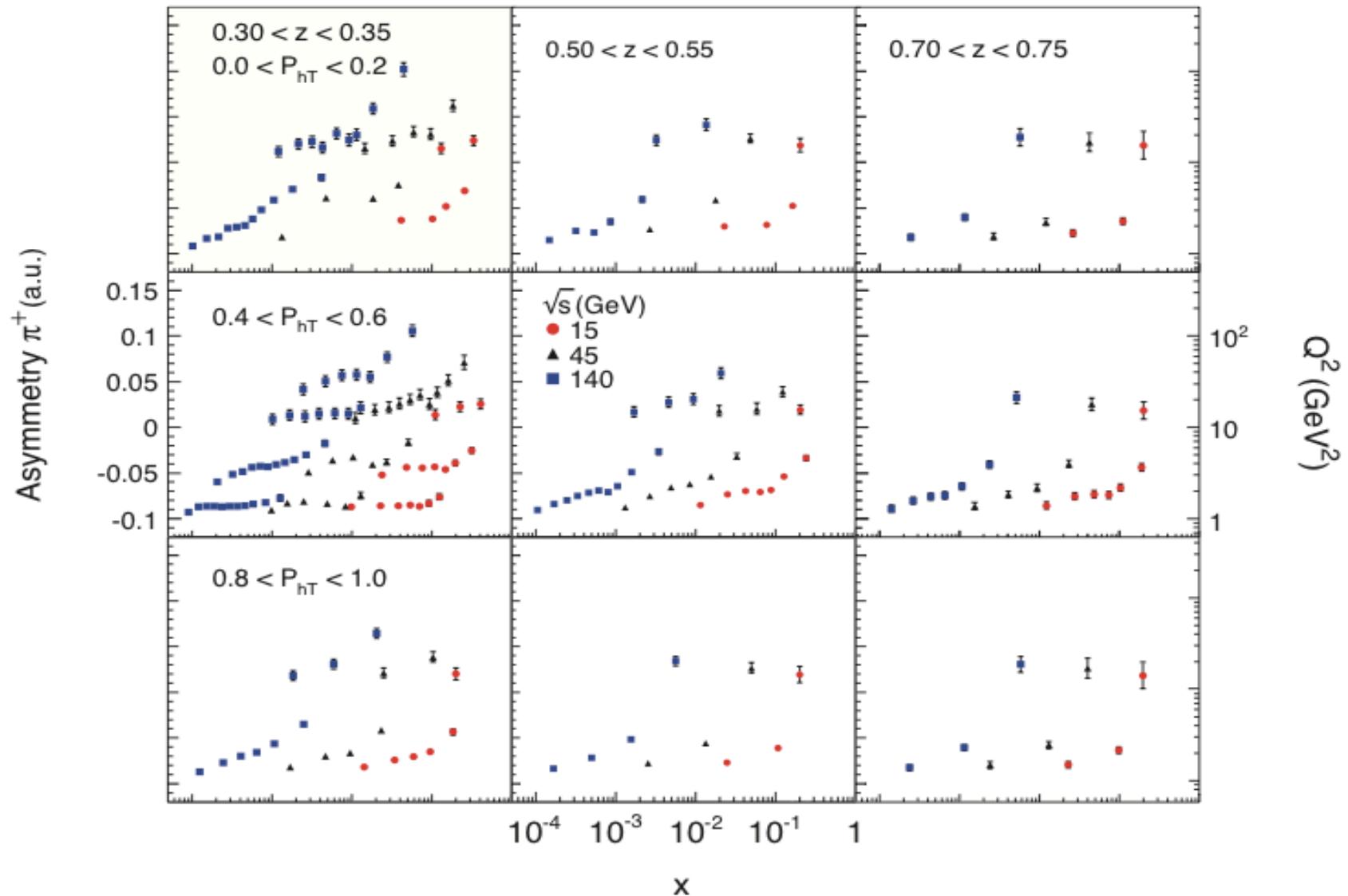
EIC-Whitepaper

$$x f_1(x, k_T, S_T)$$



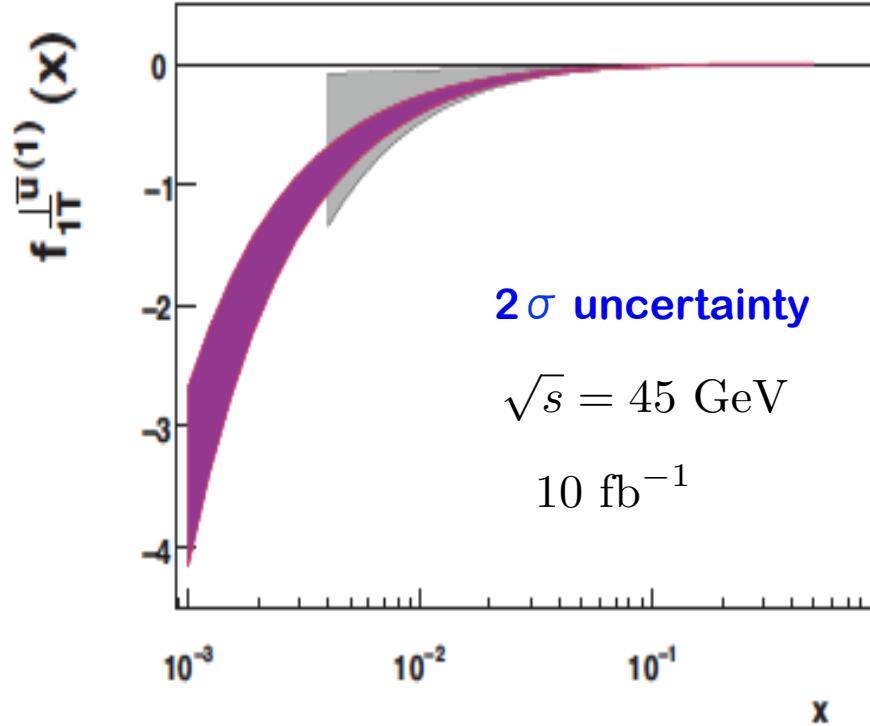
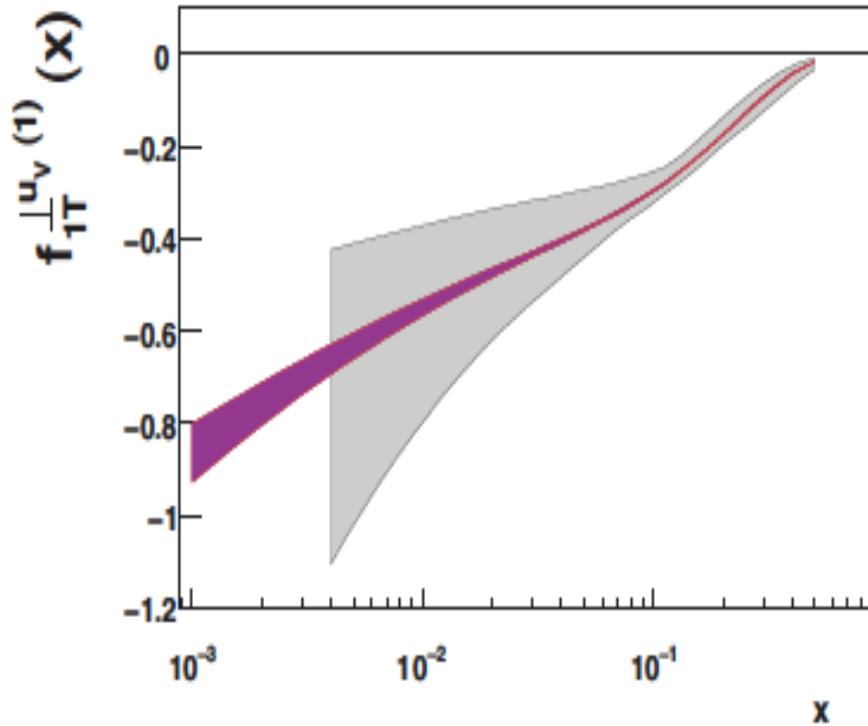
Density distribution of an unpolarized quark in a proton moving in z direction and polarized in y-direction

Precision of TMDs @ EIC



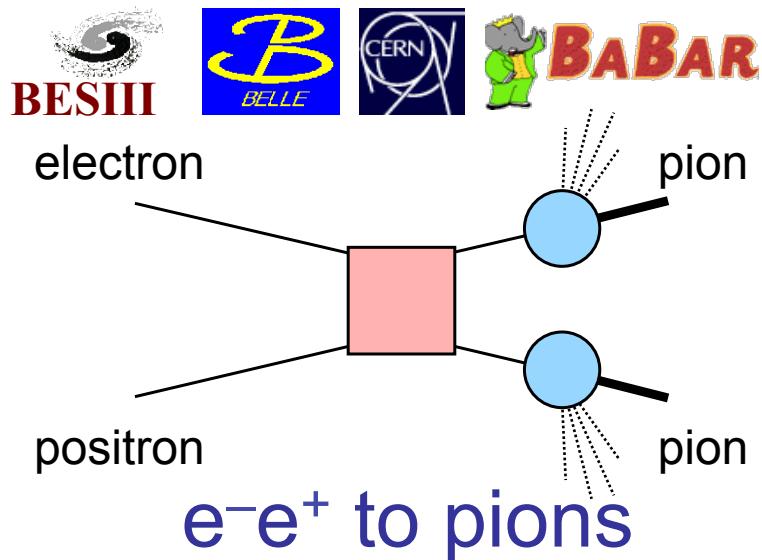
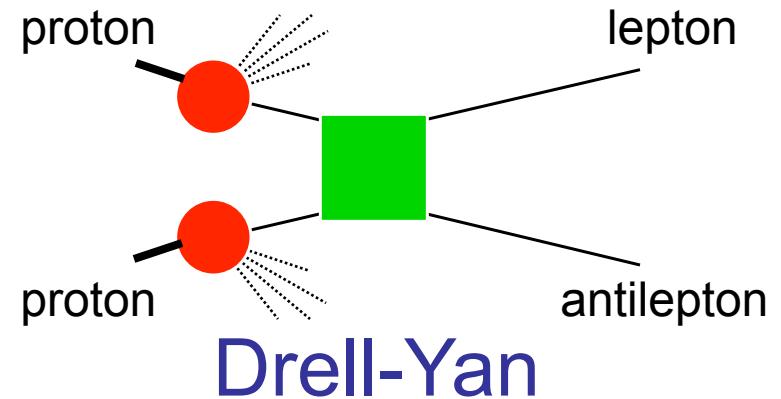
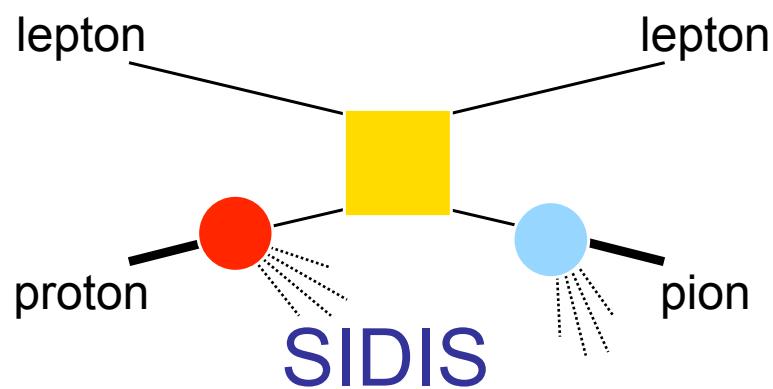
Particle ID is essential for the flavor separation of the sea

Impact on Sivers function



Precision and the range of momentum fraction x !

World effort on TMDs



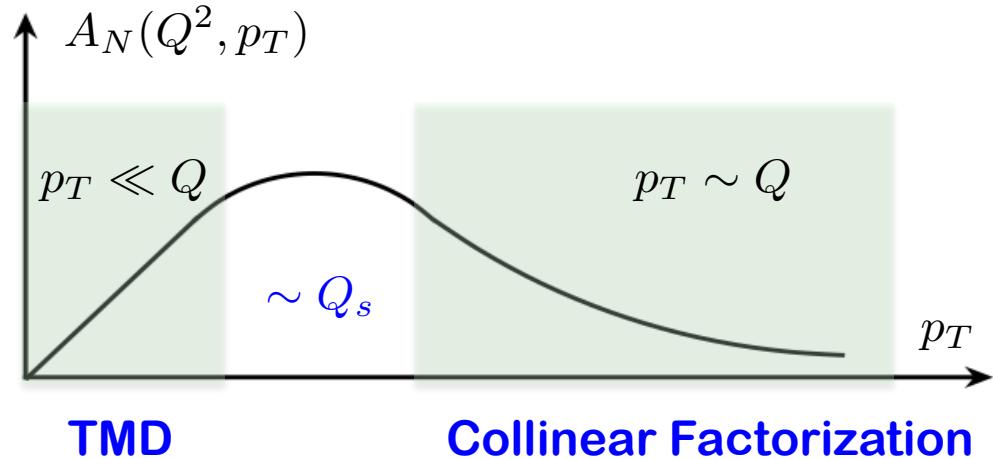
- Partonic scattering amplitude
- Fragmentation amplitude
- Distribution amplitude

$$f_{1T}^{\perp q}(\text{SIDIS}) = -f_{1T}^{\perp q}(\text{DY})$$

$$h_1^{\perp}(\text{SIDIS}) = -h_1^{\perp}(\text{DY})$$

Transition from low p_T to high p_T

- TMD factorization to collinear factorization:

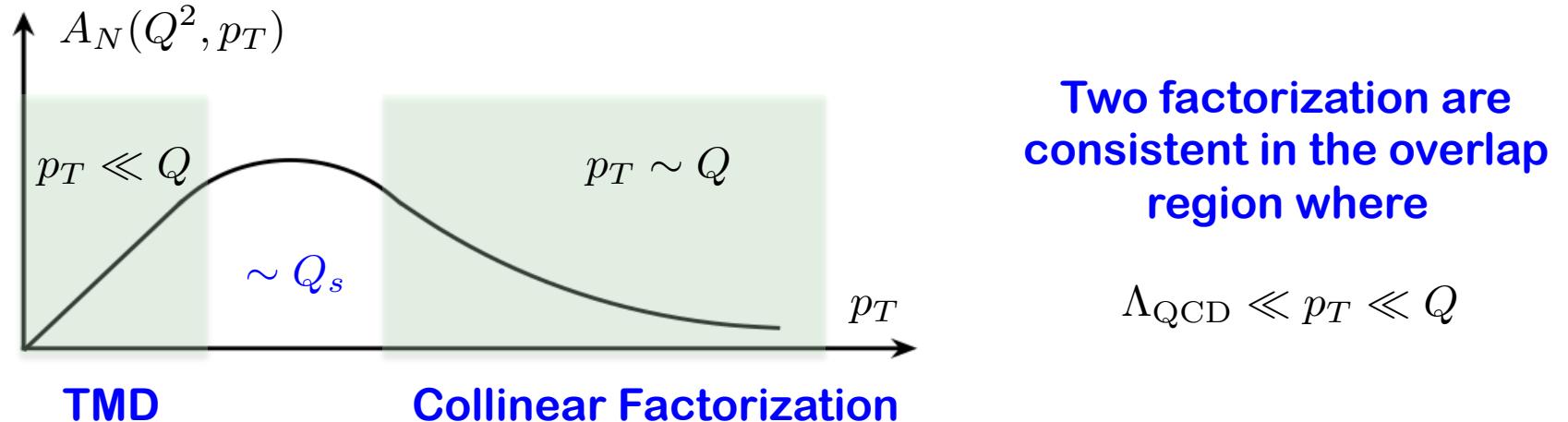


Two factorization are consistent in the overlap region where

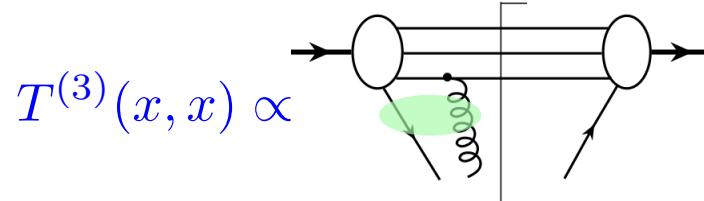
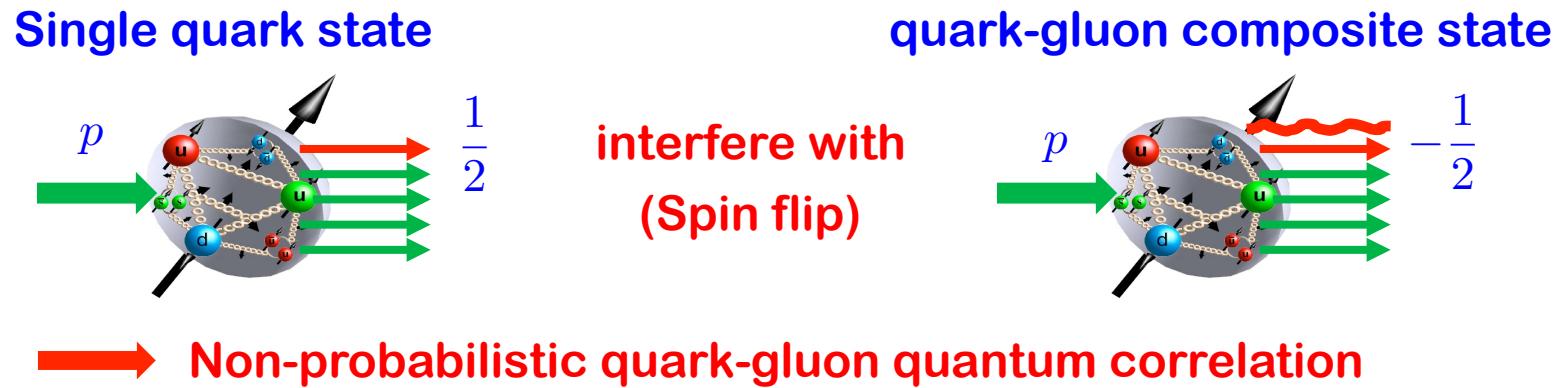
$$\Lambda_{\text{QCD}} \ll p_T \ll Q$$

Transition from low p_T to high p_T

□ TMD factorization to collinear factorization:



□ Quantum interference – high p_T region (integrate over all k_T):



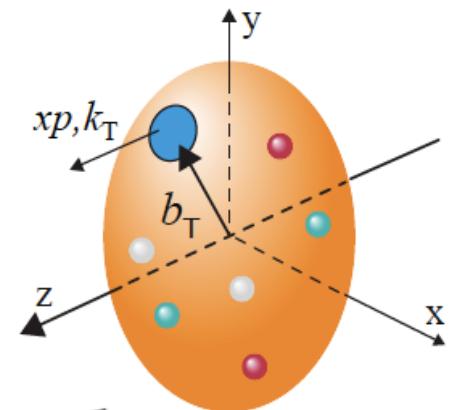
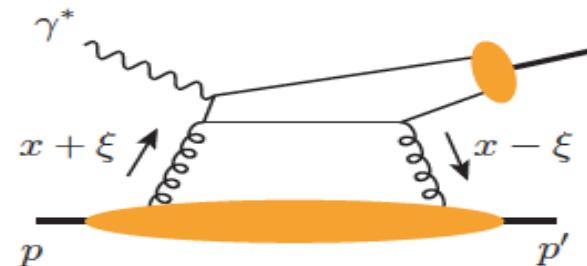
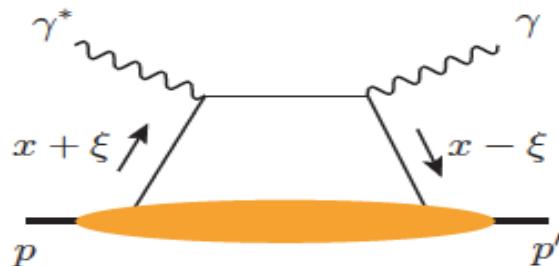
Exclusive DIS

□ Color neutral exchange:

$$\frac{d\sigma}{dx_B dQ^2 dt}$$

$$\Delta = p' - p$$

$$t = (p' - p)^2$$

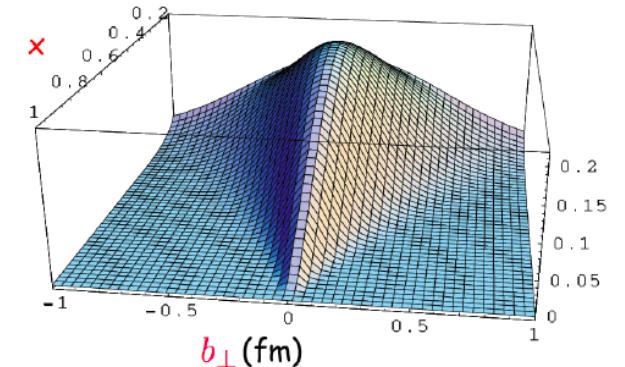


□ Theory:

- ✧ *QCD collinear factorization for scattering amplitudes – GPDs*
- ✧ *Necessary condition: $Q \gg |t|$*

□ Spatial density of partons:

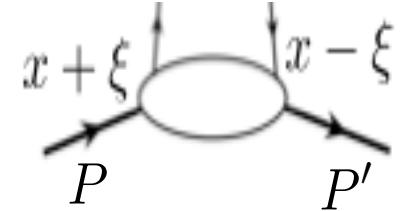
- ✧ A localized probe: $1/Q$
- ✧ Scan in transverse direction: range of t
- ✧ Quark and gluon “radius” as a function of x



GPDs – role in solving the spin puzzle

□ Quark “form factor”:

$$\begin{aligned}
 F_q(x, \xi, t, \mu^2) &= \int \frac{d\lambda}{2\pi} e^{-ix\lambda} \langle P' | \bar{\psi}_q(\lambda/2) \frac{\gamma \cdot n}{2P \cdot n} \psi_q(-\lambda/2) | P \rangle \\
 &\equiv H_q(x, \xi, t, \mu^2) [\bar{\mathcal{U}}(P') \gamma^\mu \mathcal{U}(P)] \frac{n_\mu}{2P \cdot n} \\
 &+ E_q(x, \xi, t, \mu^2) \left[\bar{\mathcal{U}}(P') \frac{i\sigma^{\mu\nu}(P' - P)_\nu}{2M} \mathcal{U}(P) \right] \frac{n_\mu}{2P \cdot n}
 \end{aligned}$$



with $\xi = (P' - P) \cdot n / 2$ and $t = (P' - P)^2 \Rightarrow -\Delta_\perp^2$ if $\xi \rightarrow 0$

$\tilde{H}_q(x, \xi, t, Q)$, $\tilde{E}_q(x, \xi, t, Q)$ **Different quark spin projection**

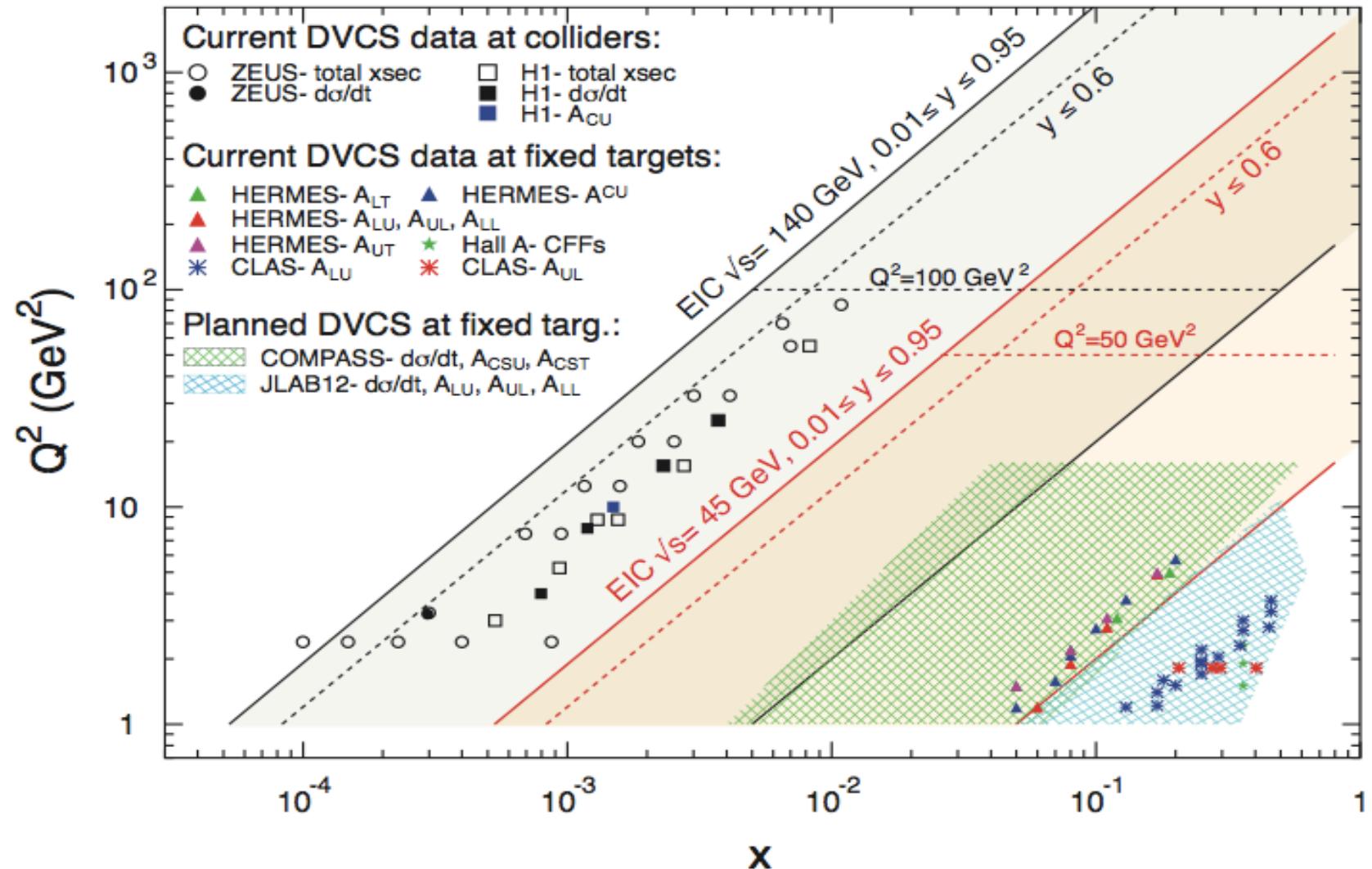
□ Total quark's orbital contribution to proton's spin: Ji, PRL78, 1997

$$\begin{aligned}
 J_q &= \frac{1}{2} \lim_{t \rightarrow 0} \int dx x [H_q(x, \xi, t) + E_q(x, \xi, t)] \\
 &= \frac{1}{2} \Delta q + L_q
 \end{aligned}$$

□ Connection to normal quark distribution:

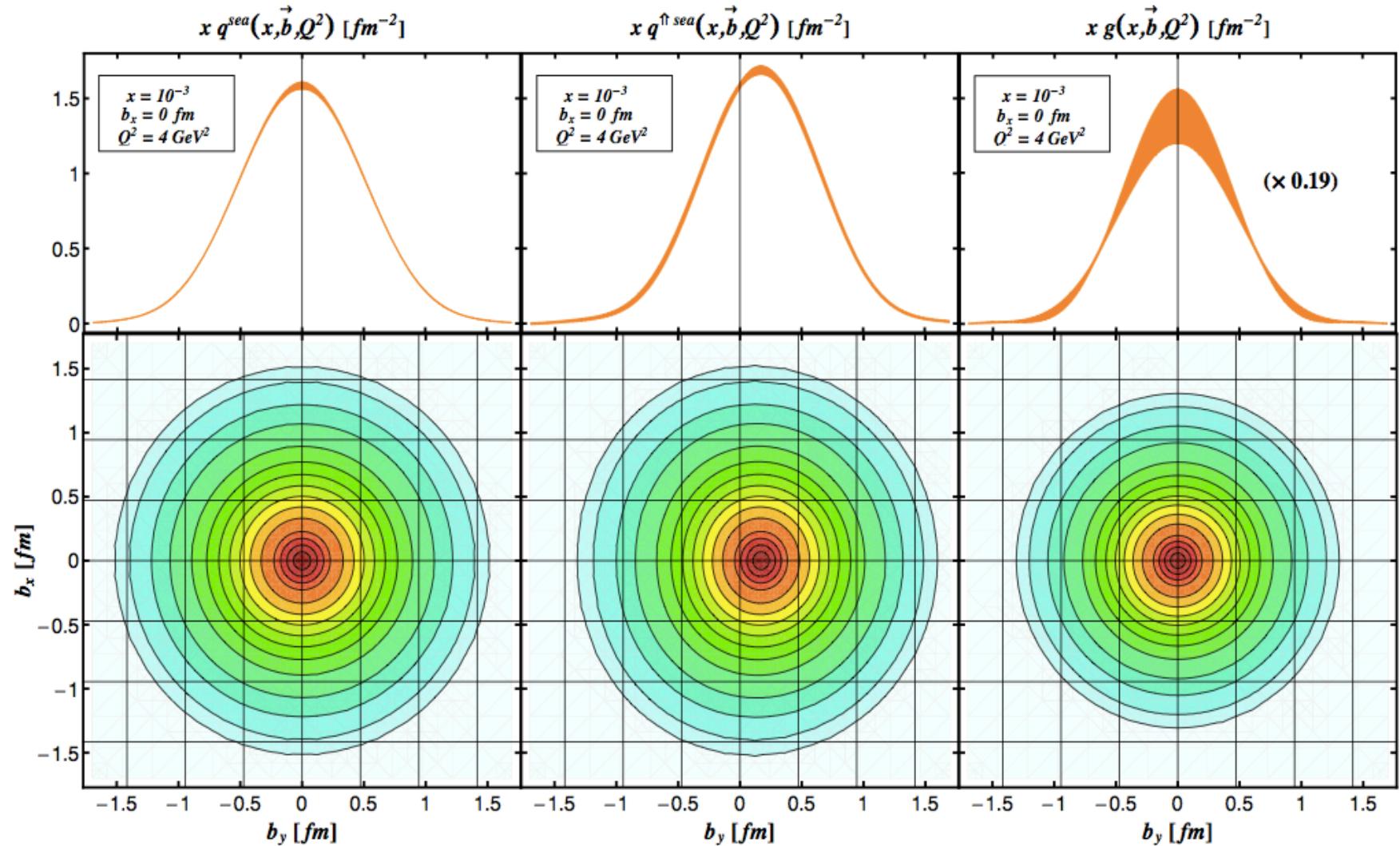
$H_q(x, 0, 0, \mu^2) = q(x, \mu^2)$ **The limit when** $\xi \rightarrow 0$

EIC coverage on GPDs



First, maybe only, measurement of polarized sea and gluon GPDs

Imaging quarks and gluons at EIC

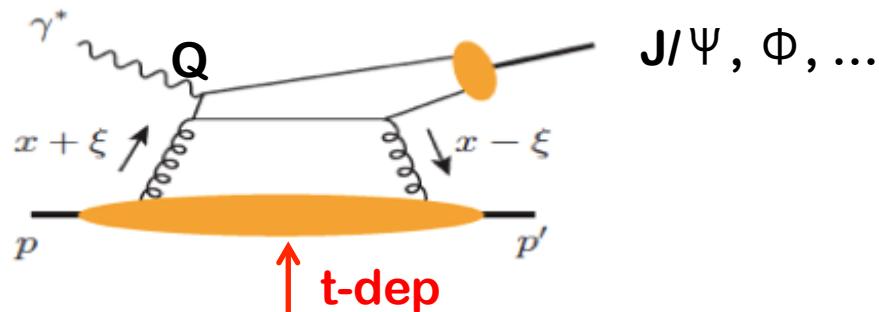


$$q(x, |\vec{b}|, Q^2) = \frac{1}{4\pi} \int_0^\infty d|t| J_0(|\vec{b}| \sqrt{|t|}) H(x, \xi = 0, t, Q^2)$$

Quark radius?
Sea radius?
Gluon radius?

Gluon tomography toward small- x

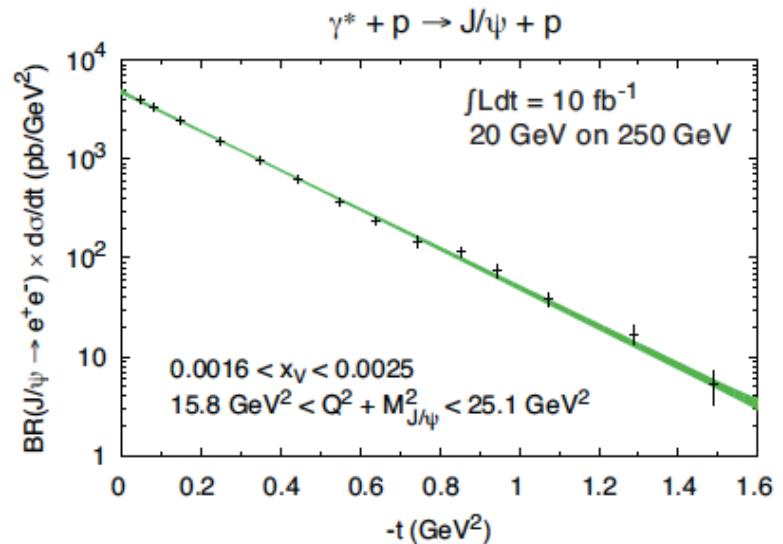
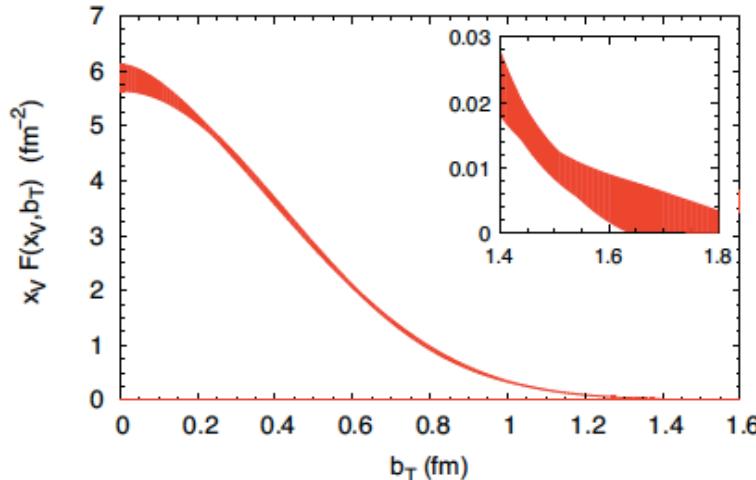
□ Exclusive vector meson production:



$$\frac{d\sigma}{dx_B dQ^2 dt}$$

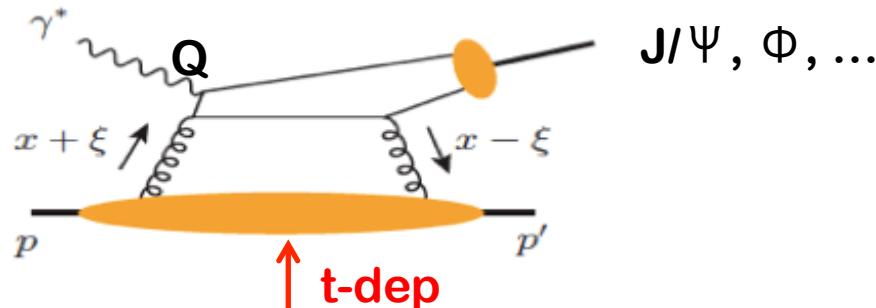
- ❖ Fourier transform of the t-dep
- ❖ Spatial imaging of glue density
- ❖ Resolution $\sim 1/Q$ or $1/M_Q$

□ Gluon imaging from simulation:



Gluon tomography toward small- x

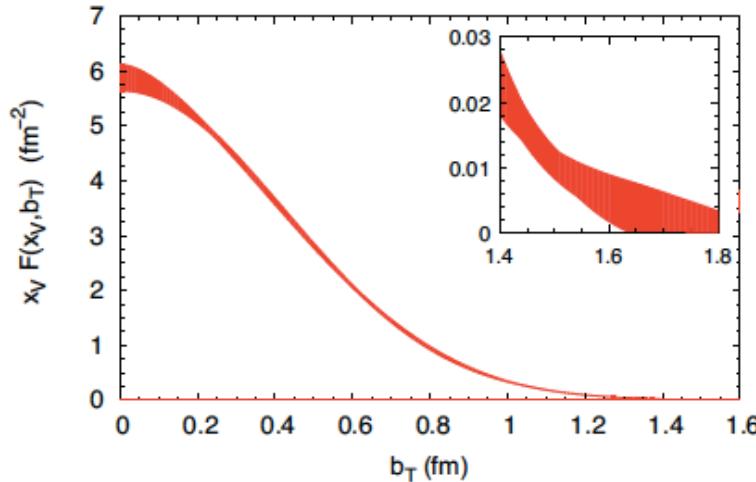
❑ Exclusive vector meson production:



$$\frac{d\sigma}{dx_B dQ^2 dt}$$

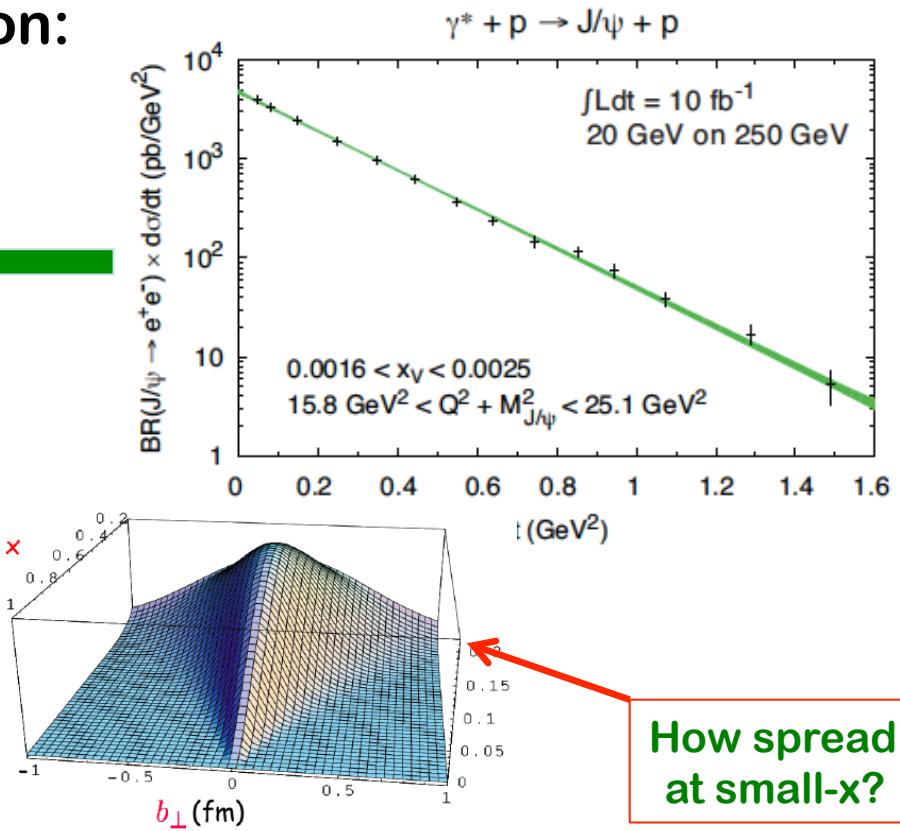
- ❖ Fourier transform of the t -dep
- ❖ Spatial imaging of glue density
- ❖ Resolution $\sim 1/Q$ or $1/M_Q$

❑ Gluon imaging from simulation:



Only possible at the EIC

Luminosity and t -coverage
are essential!

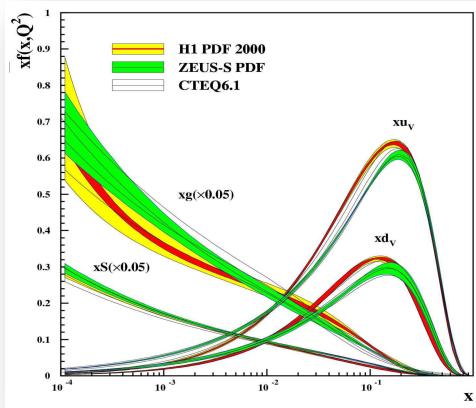


How spread
at small- x ?

Nucleon Tomography

$W_p^u(x, k_T, r_T)$ Wigner distributions

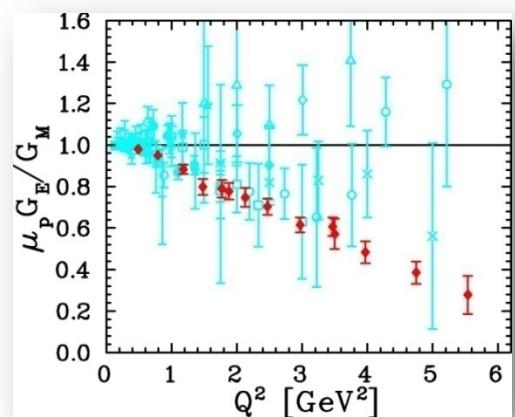
5D Dist.



PDFs
 $f_1^u(x), \dots, f_3^u(x)$

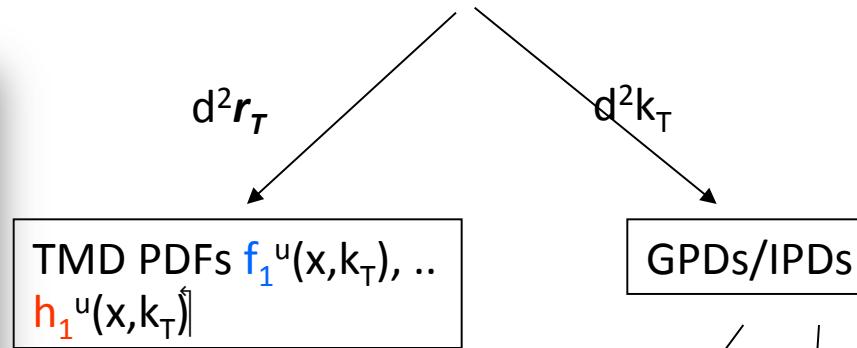
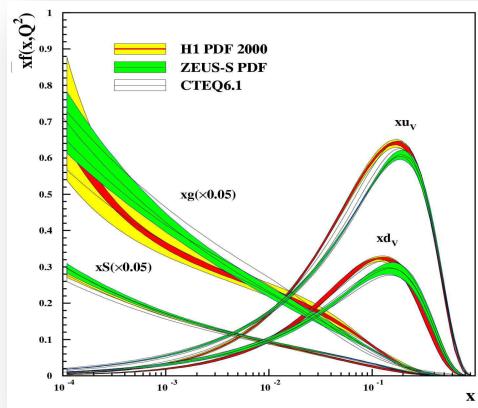
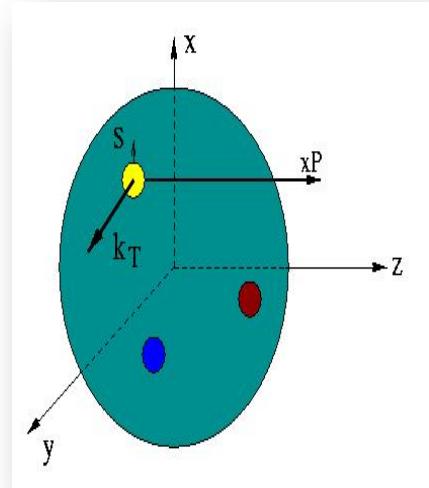
1D

Form
Factors
 $G_E(Q^2)$,
 $G_M(Q^2)$



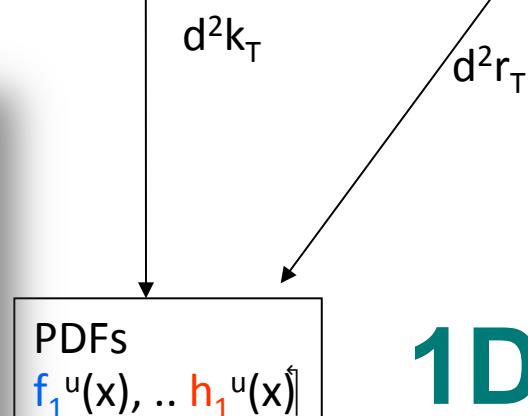
Nucleon Tomography

$W_p^u(x, k_T, r_T)$ Wigner distributions



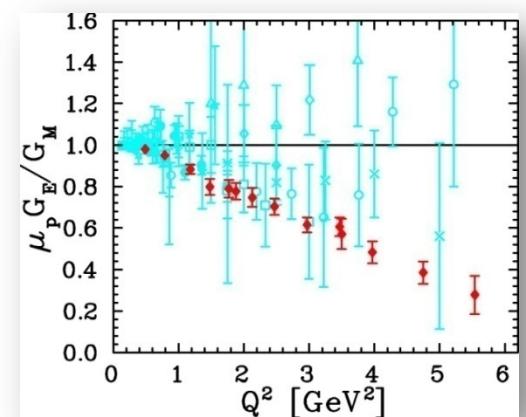
3D imaging

1D

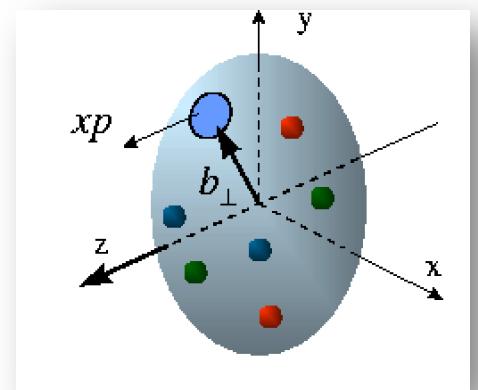


dx &
Fourier Transformation

Form
Factors
 $G_E(Q^2)$,
 $G_M(Q^2)$



5D Dist.



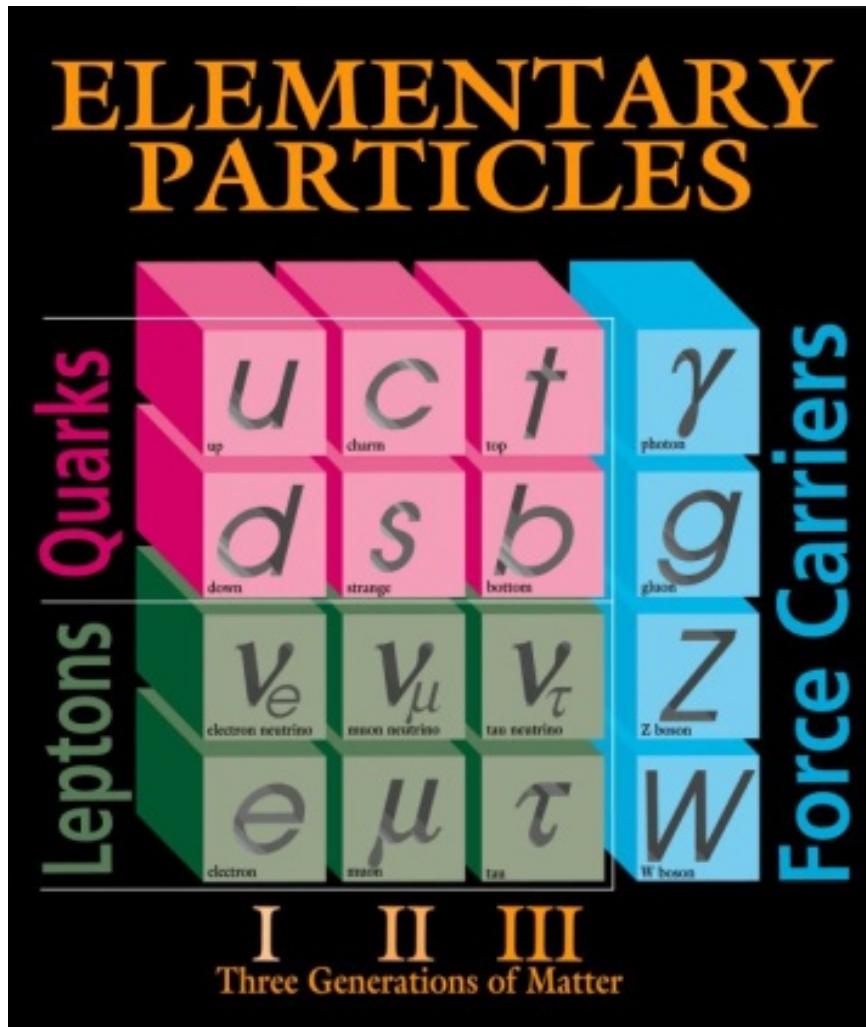
Summary

- EIC: A ultimate machine for QCD and hadron structure
- Explore the sea and gluon in 3D for the first time
- Spin is a much needed knob to explore quantum correlations
- Luminosity is important for exclusive DIS and GPDs
- EIC: A great opportunity for nuclear science

**Many Thanks to all the people
who contributed to the EIC effort!**

Backup slides

Standard Model (SM) of Particle Physics

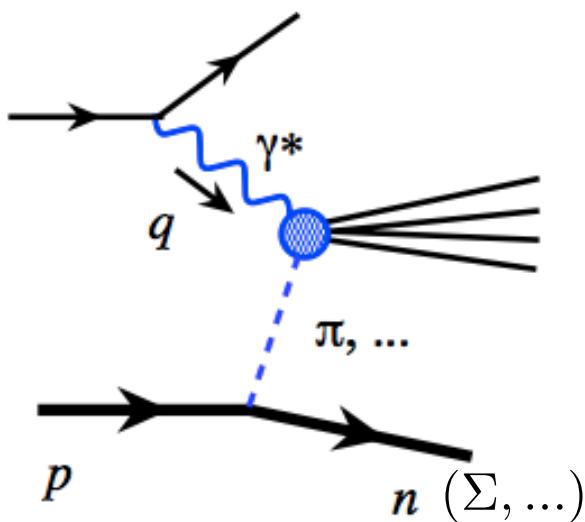


- SM very successful (no gravity)
- New physics exists (neutrino mass, dark matter, baryon number asymmetry of universe,...)
- Discovery of Higgs particle at LHC
 - almost irrelevant to nucleon mass
- Low-energy and precision frontier important and timely
- Strong interaction, QCD (quarks and gluons)
 - Remaining frontier of SM?

Structure of pions and mesons?

Pions are Goldstone bosons from
dynamical chiral symmetry breaking

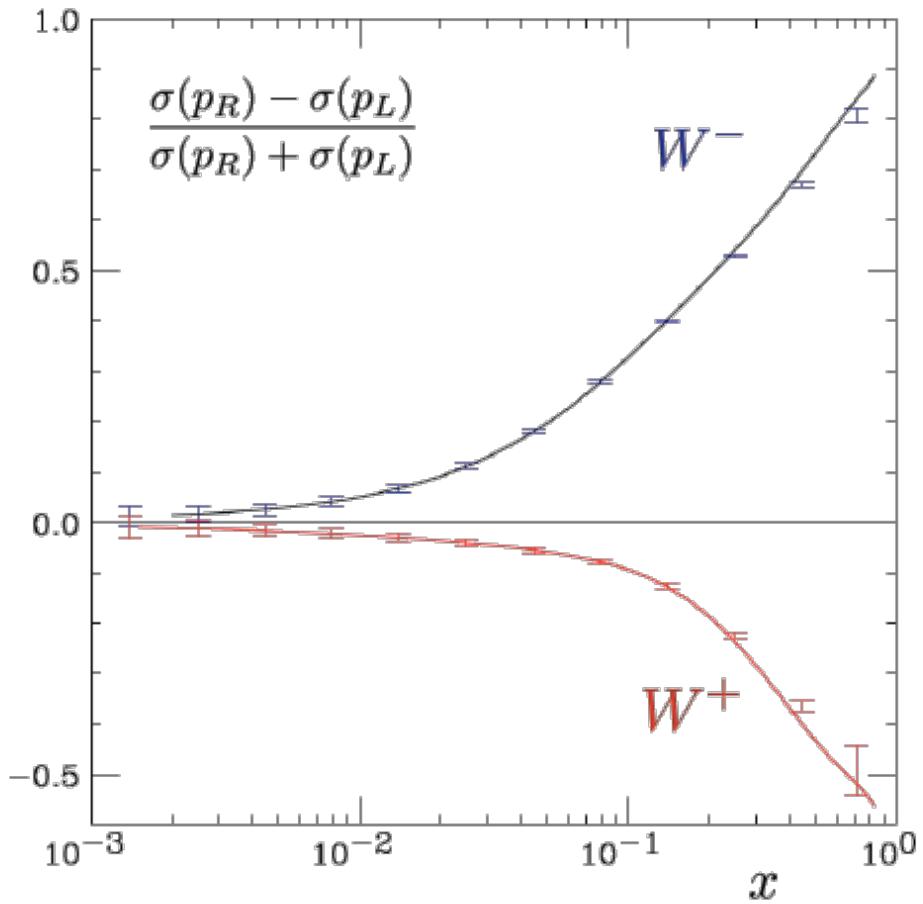
Should its structure be different from that of a typical
quark model meson?



*Valence quark distributions
of pions vs kaons?*

Ideal process for EIC?

Most promising charge current DIS



$20 \times 250 \text{ GeV}$

$Q^2 > 1 \text{ GeV}^2$

$0.1 < y < 0.9$

10 fb^{-1}

DSSV PDFs

Need to be able to reconstruct
 x, Q^2 from hadronic final-state

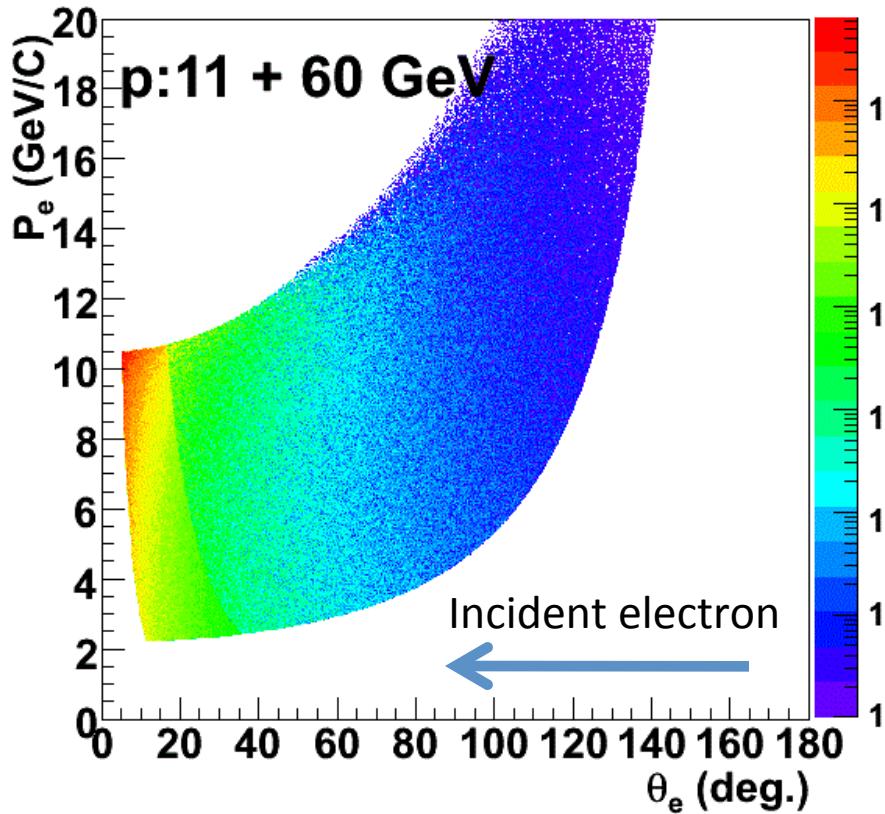
Separate up-type from down-type
PDF combinations by varying y

$$A^{W^-} = \frac{(\Delta u + \Delta c) - (1-y)^2(\Delta \bar{d} + \Delta \bar{s})}{(u + c) + (1-y)^2(\bar{d} + \bar{s})}$$

$$A^{W^+} = \frac{(1-y)^2(\Delta d + \Delta s) - (\Delta \bar{u} + \Delta \bar{c})}{(1-y)^2(d + s) + (\bar{u} + \bar{c})}$$

SIDIS Events Distributions

-- in Current Fragmentation Region



$Q^2 > 1 \text{ GeV}^2 \rightarrow \theta_e > 5^\circ$
 No need to cover **extreme forward**
 angle for electron and **extreme**
backward angle for hadrons

DIS cut: $Q^2 > 1 \text{ GeV}^2$
 $W > 2.3 \text{ GeV}$
 $0.8 > y > 0.05$
 SIDIS cut: $W' > 1.6 \text{ GeV}$
 $0.8 > z > 0.2$

